MICRO METEOROLOGICAL INVESTIGATIONS OVER A MID-LATITUDE TEMPERATE GLACIER — THE IVORY GLACIER

A Thesis presented in

partial fulfilment

for the degree of Master of Arts

in Geography

in the University of Canterbury,

Christchurch, New Zealand.

by

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1972

Frontispiece

THE IVORY GLACIER

ABSTRACT

During the summer of 1971-72 an investigation was undertaken into the components of the energy balance over a mid-latitude temperate glacier,(The Ivory Glacier), and the mass loss associated with the input of energy.

The major component of the energy balance was found to be the net radiation,however there were significant inputs of both sensible and latent heat. The proportions of each source of energy as a function of the total energy balance was found to fluctuate,with either radiation or sensible heat as the dominent source.

From measurements obtained of the mass loss at the surface,it was found that the heat sink associated with this loss,was,on all but two occasions,of less magnitude than the computed heat input from the energy balance components. This difference in the two values has been attributed to an unmeasured evaporative loss which was not accounted for by the conversion of the mass loss to energy units. On the two days of greater heat loss than gain,it is suggested that the difference was attributable to mechanical erosion of the granular ice by rainfall.

Rainfall was not found to be significant in the energy balance,except during intense rainfalls when it was found that this parameter could contribute up to 87 ly day $^{-1}$ to the total energy input to the surface.

An attempted correlation between the mass loss and the standard meteorological parameters was unsuccessful, however more success may have been achieved had the parameters been weighted.

ACKNOWLEDGEMENTS

The work undertaken in this study could not have been accomplished without the aid of many people, too numerous to mention here. However, the help received from some must be mentioned.

Firstly my thanks must go to the New Zealand Ministry of Works Hydrological Section, for the logistic support given, and also to the Geography Department, University of Canterbury for allowing me to use their equipment.

For their help and companionship in the field my grateful thanks go to first, my research assistants Miss Toni Izzard and Mr Bruce Dixon, and secondly to Dr. Peter Anderton and the other members of the Hydrological Section of the Ministry of Works.

For the willing assistance given by members of the staff of the Geography Department, University of Canterbury, in the unravelling of many problems my thanks are expressed, and especially to Dr. John Hay, my supervisor for his aid in the preparation and maintenance of equipment, before and during the field work, and for his critical appraisal of parts of the text.

My thanks go also to Mr David Harrowfield for his assistance during the latter stages of the preparation of the manuscript, and to my typists - Miss M. Belcher, Mrs E. Wills and Mrs J. Wyld for their most patient co-operation.

The many long hours spent in preparation were made more bearable by the wit of those in G.5. and my appreciation goes to them, my fellow students.

Lastly I must mention the moral support given to me by my Father and my Fiancee who have borne with me throughout.

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CHAPTER

I

INTRODUCTION

I. GENERAL

The inter-related nature of glaciers and climate has been recognised since the earliest research into the physical characteristics of glaciers in the 18th century; but it was not until the late 1890's and early 1900's, that any emphasis was placed on this inter-relationship as being a possible means of gaining a better understanding of what a glacier is and how it exists. Hamburg in the 1890's, was the first to expound the idea that to understand the advances and retreats of glaciers it is first necessary to study how both accumulation and ablation occur, (Wallēn 1948). These ideas were not expanded however until Sverdrup, in 1934, undertook investigations into the transfer of energy between the atmosphere and surface of a glacier during the melting season, in an attempt to ascertain the relative importance of the various energy sources in explaining a measured change of a glacier's surface. The techniques put forward by Sverdrup, have since undergone considerable refinement especially by such investigators as Wallēn in late 1940's, Hoinkes in the 1950's and Havens and Sagar in the 1960's, but the theories used have remained basically the same.

At the present time there are two basic approaches to the study of the influence of climate on the mass balance of a glacier. The macroclimatological approach attempts to discover the relationships that exist between a glacier and the climate of the area in which it is situated. This approach takes a general overview of the climate and attempts to evaluate glacial fluctuations in terms of easily measured climatic parameters. The other approach, the microclimatological approach, concentrates on the energy exchange at the surface of the glacier, and the processes which bring about this exchange. The latter of the two approaches, however, has one distinct drawback in that it is restricted in its applicability to the small spatial and temporal scales at which this type of study usually has to concentrate for economic reasons. The instrumentation used needs to be precise and this type of instrument is usually costly. Further cost is also incurred with the use of this approach because the temporal sampling intensity required with such a study means that manned stations, often in an isolated area, need to be established. However, although these drawbacks do exist, this latter approach is the more valuable because from its use, a greater understanding can be gained of the relationship between the climate and its effect on the glacier.

The microclimatological approach involves the consideration of:

(a) The net gain or loss of radiative energy (R) from the component parts of the radiation balance. These being incoming and outgoing short-wave radiation and incoming and outgoing long-wave radiation.

(b) The net gain or loss of sensible heat (H) by the process of eddy conduction from or to the air; if the temperature increases with height in the former case and if the temperature decreases with height in the latter, provided that in both cases the air flow is turbulent.

(c) The net gain or loss of latent heat (L E) by the processes of condensation of water vapour at the surface (increasing vapour pressure from the surface) or the evaporation of water from the surface (decreasing vapour pressure gradient), provided again that the air flow is turbulent.

(d) The net gain or loss of heat by the surface to the underlying snow or ice (M). A downwards transfer (away from the surface) of energy occurring if the temperature decreases with depth and on upward transfer (towards the surface) occurring if the temperature increases with depth.

(e) The heat gain from rainfall by refreezing of rainfall at the surface or by the actual heat content of the rain itself (P).

(f) The heat loss due to melting (A).

These processes can be represented by the equation:

$$R + H + LE + M - A = 0$$

II. AIMS

Although a large part of microclimatological approach is based on the '....dynamics of turbulent fluids... (this) theory is difficult and many problems are still unsolved.' (Paterson (1969), P. 46). This approach was adopted in the present study because of its usefulness in enabling the ablation occurring at the glacier's surface to be gauged in terms of the relevant heat inputs.

The aims of this study, following on from the use of the energy balance approach, were twofold.

(1) To attempt to ascertain the sources of heat input at the surface of the Ivory Glacier, and their magnitude and relative contribution to the observed surface change, during a portion of the ablation season.

(2) To attempt to find any significant and meaningful relationships between the more easily measured climatic variables (e.g. rainfall, temperature, cloud cover etc.) and the observed surface change so that the latter might be estimated from a combination of the former without having to undertake the involved analysis required by the energy balance approach.

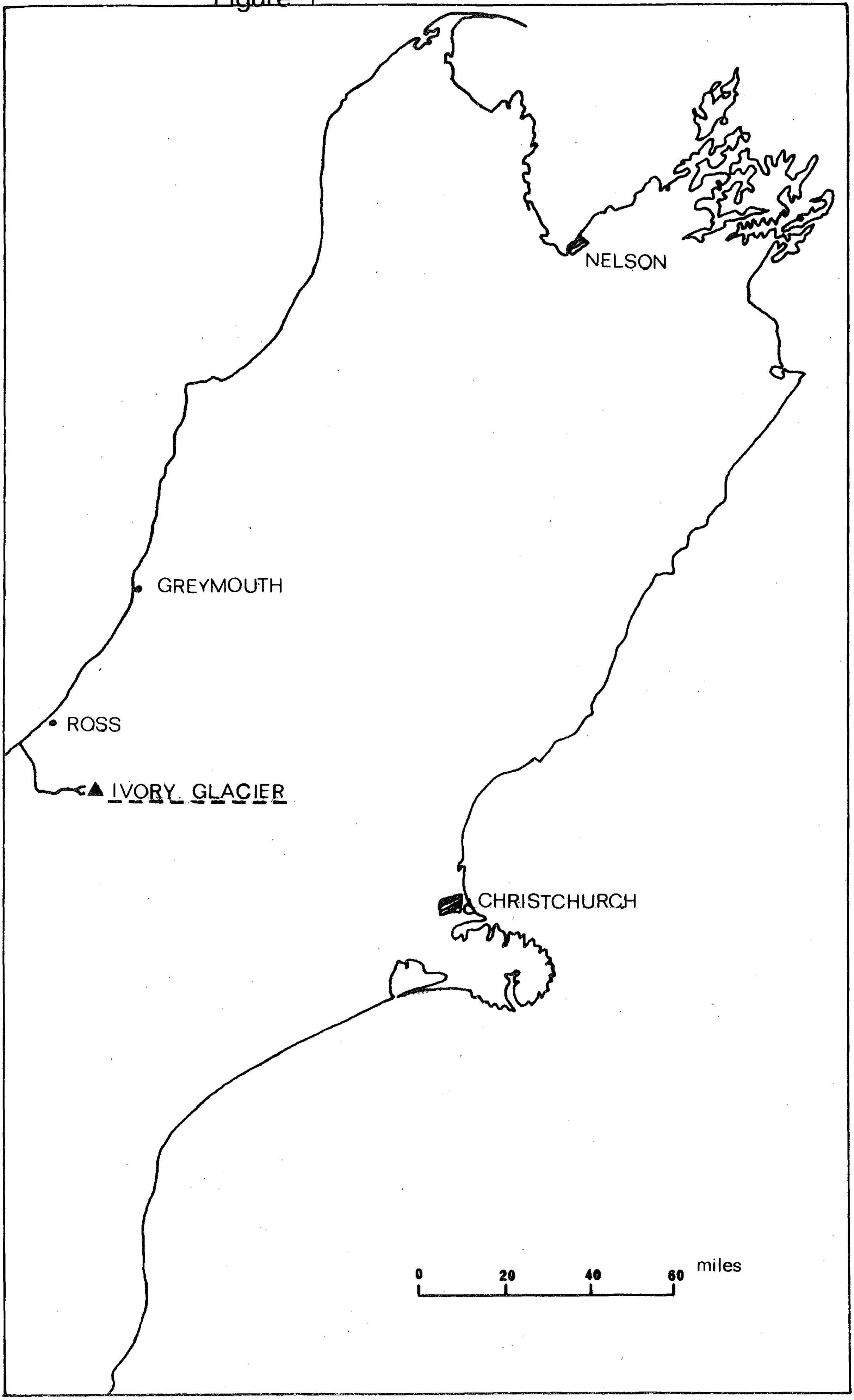
III THE STUDY AREA

A. THE IVORY BASIN

The Ivory Basin is an almost circular cirque located in the head waters of the Waitaha River, South Westland (New Zealand), at a latitude of 43° 07' S, in a position just to the west of the main divide of the major mountain system of the South Island (The Southern Alps) and approximately 44 km south of Hokitika, (See Figure 1). The basin is a classic example of a hanging valley situated some 100 to 150 m above the main river valley. It is surrounded on three sides by steep biotite schist slopes and is orientated almost directly north-south with the highest point of its periphery ('The Tusk', 2080m) being at its most northerly point. The glacier

Figure 1: The location of the Ivory Basin

Figure 1



NELSON
GREYMOUTH
ROSS
IVORY GLACIER
CHRISTCHURCH
0
20
40
60
miles

comprises 60% of the total area (2.37 km^2) of the basin, (See Figure 2). It descends in two moderately sloping stages separated in its mid portion by a relatively flat to gently sloping area which covers the width of the glacier and extends for approximately 400 to 500 m along its length.

B. THE STUDY SITE

The instrument site (see Figure 3) was located approximately 400 metres from the glacier's terminus at an elevation of 1500 m on a portion of the glacier where the gradient was low (1 in 20). This site was chosen because of the relatively horizontal surface (compared to the rest of the glacier) in its vicinity and was situated as near to the centre line of the glacier as was possible to minimise any localised effects that may have been induced by proximity to the valley walls.

The surface of the glacier at this site changed considerably throughout the study period, progressing from a relatively smooth snow surface at the commencement of the study (see plate 1) to an indented ice surface by the end of the study period (see plate 2).

IV THE OBSERVATIONAL PROGRAMME

The study period extended from November 17 1971 to February 14 1972 however there was a break of two weeks (between December 22 1971 and January 4 1972) to enable instrument malfunctions to be corrected. This two week period was longer than anticipated because adverse flying conditions delayed the return to the glacier.

The full observational programme was as follows:

(1) Observations obtained every 3 hours from 0600

Figure 2: The Ivory Basin showing the position of the Instrumental site.

Figure 2

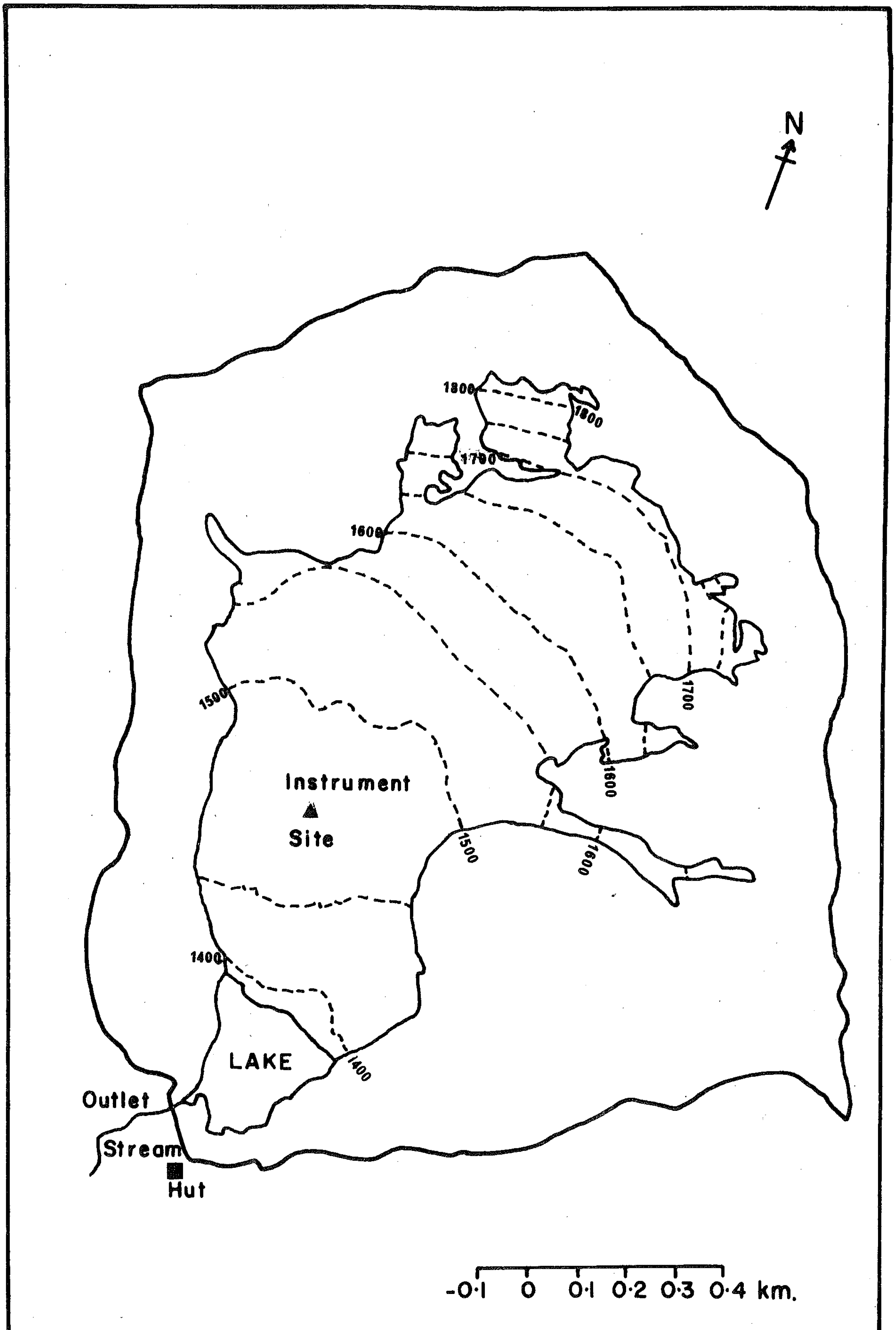
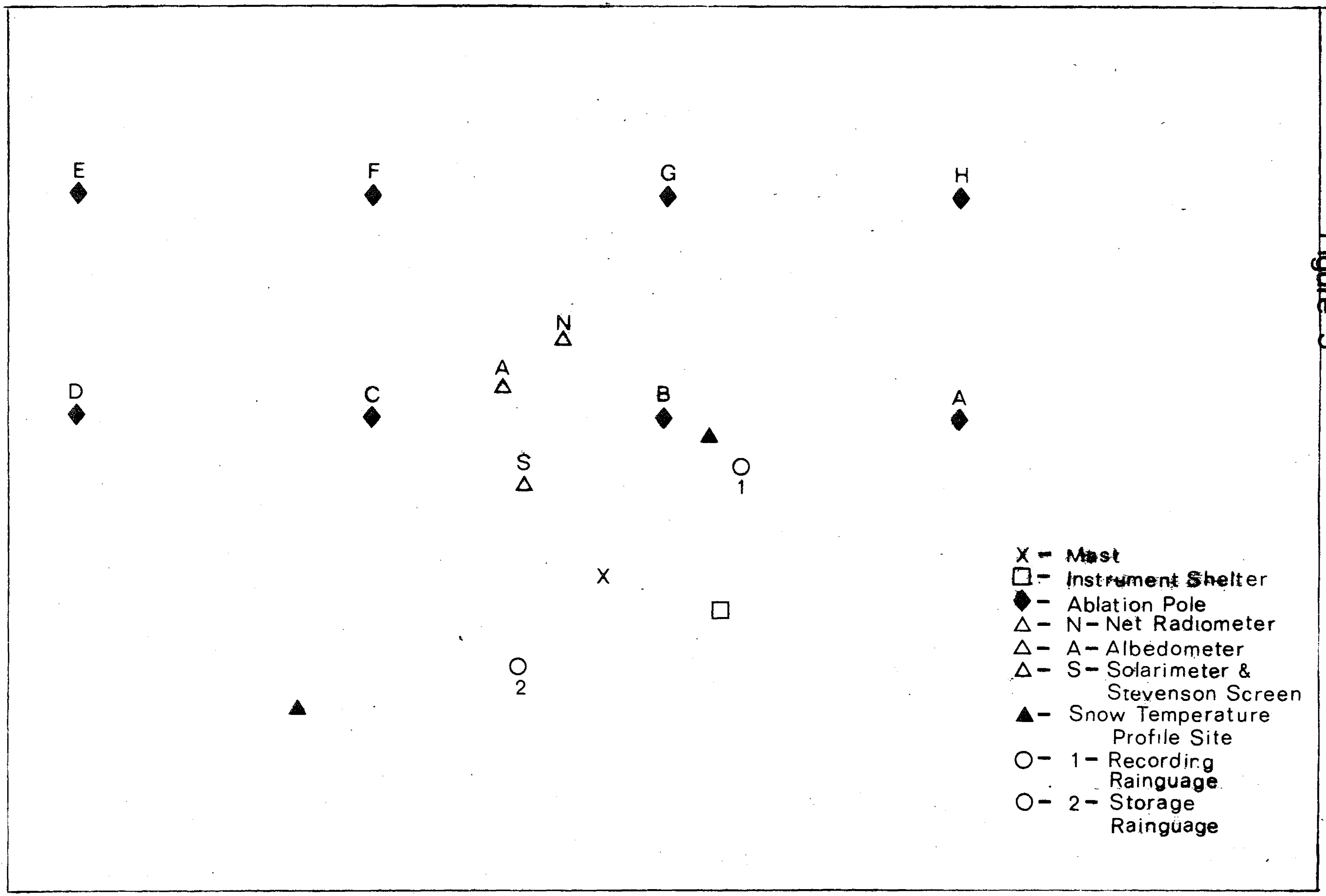

N
1800
1800
1700
1600
1500
1700
1600
Instrument
Site
1500
1600
1400
LAKE
1400
Outlet
Stream
Hut
-0·1 0 0·1 0·2 0·3 0·4 km.

Figure 3: The Lay-out of the study site.



E
F
G
H
N
A
D
C
B
A
S
1
X
2
X – Mast
□ – Instrument Shelter
◆ – Ablation Pole
△ – N – Net Radiometer
△ – A – Albedometer
△ – S – Solarimeter & Stevenson Screen
▲ – Snow Temperature Profile Site
○ – 1 – Recording Rainguage
○ – 2 – Storage Rainguage

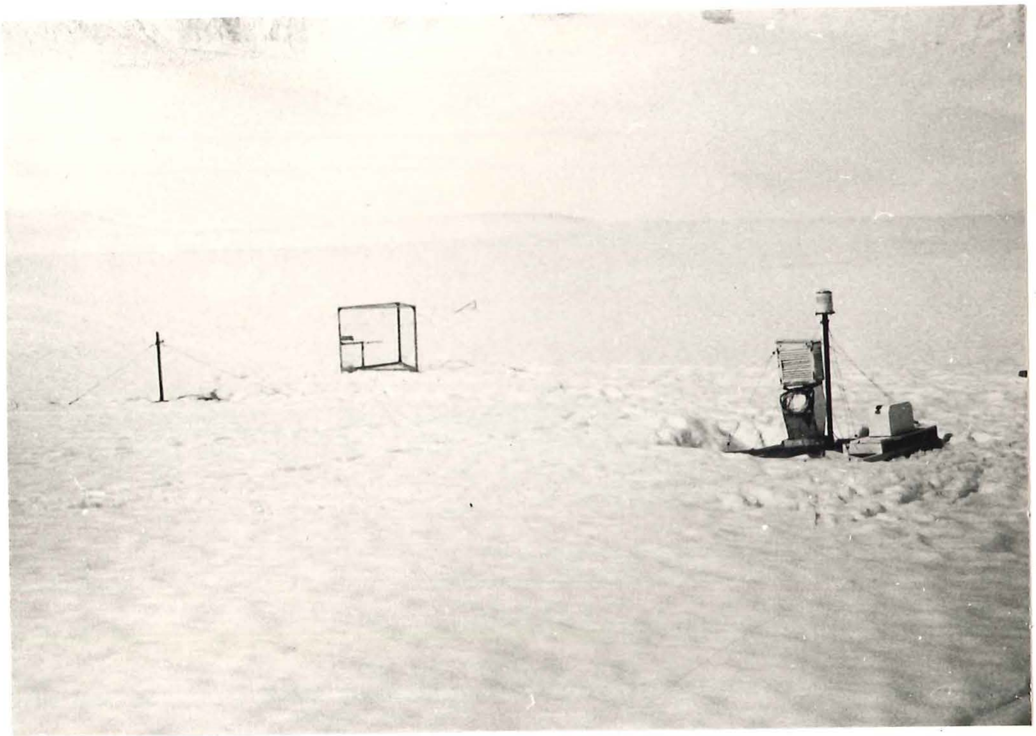
Figure 3

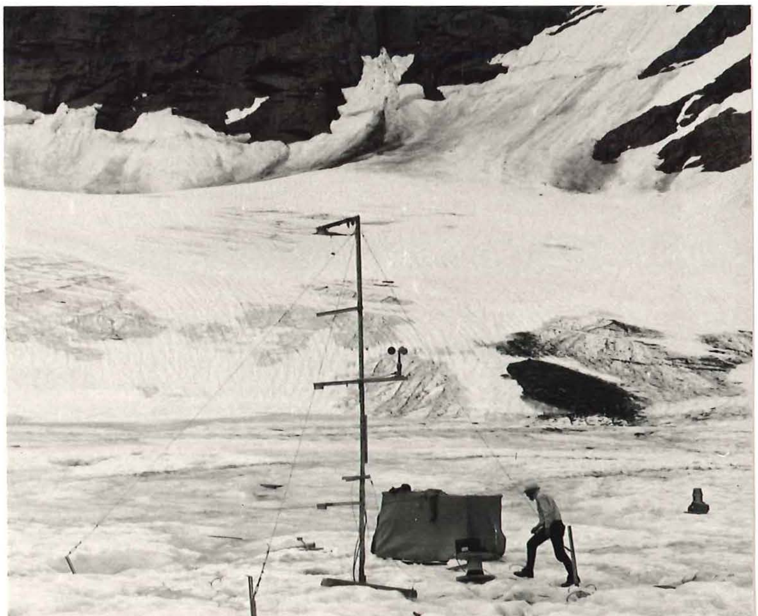
Plate 1

Early season smooth snow surface (December 4)

Plate 2

Late season rough ice surface (February 12)





to 1800 hours of:

(a) Instantaneous values for:

(i) Temperature at 1.2 metres above the surface

(ii) Humidity at 1.2 metres above the surface

(iii) Cloud Cover - amount (in eighths), type and height

(iv) Pressure - recorded in millibars directly

(v) Albedo - recorded every 3 hours and at other appropriate times i.e. when cloud conditions were stable.

(b) Totalised values for:

(i) Net radiation - totalled since the last observation and measured 1 m above the surface

(ii) Short wave radiation income - totalled over the period since the last observation and also measured at 1 m above the surface.

(iii) Wind run totalled over the period since the last observation.

(iv) Wind run - totall of a 10 minute interval at each observation time.

(2) Daily measurements:

(a) Precipitation - manual recordings from a storage gauge and weekly continuous records from a recording gauge.

(b) Maximum and minimum temperature - recorded in a standard climate screen (Stevensons Screen) at 0600 hrs.

(c) Ablation - measured at 8 poles.

(3) Measurements obtained at irregular intervals:

(a) Heat flow through the snow pack, and snow pack temperatures at various depths (10, 20, 50 and 100 cm)

(b) Wind profiles - obtained when conditions were favourable for the use of the anemometers available.

(4) Continuous records of humidity and temperature at three heights (1.2, 2.8 and 5 metres above the surface), each height being sampled once every eight minutes.

A description of the instruments used to undertake this study will be given in the relevant Chapters.

V. OUTLINE

The method used to measure the change in the height of the glacier's surface (surface change) and the data obtained, will be outlined in Chapter Two along with attempts to account for the spatial and temporal variations in the measurements obtained.

Chapter Two will deal with the components of the energy balance, how they were measured and the methods used to calculate the relevant fluxes. A short discussion will then be undertaken on the comparison between the energy input (from the energy balance calculations) and the heat sink associated with the measured surface change.

In Chapter Three, a description of the results gained from a comparison of the daily surface change values and the daily mean and total values of various climatic parameters was undertaken to find if any relationships exist

Chapter Five will be the conclusion.

CHAPTER

2

Surface Change

I Introduction

The term ablation has been defined to mean both the processes by which material is removed from a glacier, and the amount of material removed. Paterson (1969 p.29) defines ablation as 'all processes by which snow and ice are lost from the glacier' while Østrem and Stanley use the following definition by Ahlmann in 1948,

> 'Glacier ablation comprises all material which is removed from the glacier by melting, evaporation, calving and wind action.'
> (Østrem and Stanley, 1969, p. 33)

In the present study ablation will be considered in terms of both these definitions (i.e. the removal processes and the material removed).

The processes responsible for the removal of snow and ice consist of melting and its associated run off, evaporation and sublimation, iceberg calving, and the removal of snow by wind action. However for the purposes of an energy balance study of a valley glacier only melting, evaporation and sublimation are of significance for 'wind action is negligible' (Østrem and Stanley, 1969, p.33) and iceberg calving is only of importance if the glacier is being considered in its entirety, a consideration that is not usually applicable to energy balance studies because of the limited spacial coverage which is typical of such studies. As these processes (i.e. melting, evaporation and sublimation) are, for the purpose of an energy balance study, considered in terms of the heat energy that they require, the ablation, as defined by Paterson may be expressed in terms of the heat energy involved in these processes. The values for the ablation are then calculated by the use of the energy balance equation using the ablation term (A) as a residual, thus

$$A = R + H + LE + P + M$$

For the purpose of this dissertation, the term <u>ablation</u> will only be used when referring to the values obtained from the energy balance equation. Values for the actual loss or gain of material from the vicinity of the study site, expressed in terms of mass (i.e. water equivalent values), will hereafter be referred to as <u>surface change</u> in order to distinguish them from the ablation.

The present chapter is concerned with a description and qualitative analysis of the surface change values and the methods used to acquire them. A discussion of the ablation and the relevant sources of energy, their magnitude and importance is to be found in Chapter 3.

II Methods

A. The Measurement of Surface Change

To obtain values for the surface change, one basic method has been used by most investigators of glacial energy balances. This method involves placing a marker (usually a simple stake) on or into the surface of the glacier. This stake acts as a reference against which any surface change can be gauged, provided the stake remains stationary in the vertical axis. Any surface change is calculated by measuring from the glacier's surface to a fixed point on the stake (usually the stake's top).

The surface change values used in the present study were obtained from a network of eight poles (see fig. 3) positioned just to the north of the main instrument site. The poles were tubular and constructed of Poly Vinyl Chloride (P.V.C.) of 2 cm diameter, with a wall thickness of 3 mm. The respective length of each pole is given in table 2:1. As poles A and B were below the surface, a short length of the same material was attached to each by means of tape until the main pole was visible above the surface.

Once the snow cover had ablated to the extent that the poles would no longer remain upright, it was necessary to reposition them by drilling onto the ice with a Spire corer. It is possible that a source of error in the surface change values may have resulted from this as a consequence of the drilled hole being considerably larger in diameter than the poles and tending to fill with water shortly after being drilled. The water that accumulated in these holes was not observed to refreeze. Since one cannot expect two bodies at different temperatures, no matter how small the difference in temperature may be, to maintain their respective temperatures over long periods of time, it must be assumed that the higher temperatures of the water caused melting at the sides and bottom of the holes. However, no values were obtained to ascertain whether this phenomina did occur but the possibility of its occurrance must be borne in mind. Sinkage can also be caused by the pole

TABLE 2 : 1

SNOW DEPTH AT EACH POLE AS RECORDED ON NOVEMBER 29, 1971

Pole	Depth of "New Snow" [1] (cm)	Depth of Glacier Ice (cm)	Length of Main Pole (cm)	Additional Length (Taped on) (cm)
A	61	422	400	+ 30
B	57	402	400	+ 10
C	54	350	400	
D	50	368	400	
E	51	381	400	
F	50	349	400	
G	52	434	600	
H	51	366	400	

[1] The "new" snow is that snow which fell between November 23 and November 28 (after the commencement of the study period).

absorbing heat energy. If this energy is readily transmitted throughout the length of the pole, it will cause melting where the pole contacts the snow or ice and this could cause the pole to sink relative to the surface negating its effectiveness as a reference. Thus care must be taken to ensure that the material of which the pole is constructed has a low heat capacity and a low potential for heat absorption and conduction.

Metal poles have been used extensively in glacial energy and mass balance studies, and their use is recommended by some investigators (e.g. Østrem and Stanley, 1969). They have also been used in New Zealand in ablation studies undertaken by the New Zealand Ministry of Works but were found to melt rapidly into the surface once exposed to solar radiation(1) and for this reason, were not used in the present study. Bamboo has also been extensively used for ablation poles because of the material's low heat absorption, conduction and capacity characteristics. It also has the added advantage of being easily transported because of its light weight. However, bamboo is fragile and floats on water, two characteristics which rule out its use on a glacier such as the Ivory where high winds and water filled holes were expected. The P.V.C. poles that were used were somewhat revolutionary in that it is understood by the author that this material has seldom, if ever, been used for this purpose before. The idea for the use of P.V.C. originated within the Snow Survey Section of the New Zealand Ministry of Works who have found it ideal during previous seasons of work undertaken on the Ivory and Tasman Glaciers.(2)

(1) Pers. Com. Dr P. Anderton, N.Z. Ministry of Works, Hydrological Survey

(2) Pers. Com. Dr P. Anderton, N.Z. Ministry of Works, Hydrological Survey

P.V.C. plastic is a strong rigid material that is easily transported. It also has the advantage of not floating in water but to the author's knowledge its heat capacity, absorption and conduction characteristics, as they relate to its use in ablation studies, have never been tested. However, from general observations of its performance in the field, both by the author and personnel of the Snow Survey Section, it would appear that the P.V.C. is not greatly affected by heating as a consequence of the absorption and conduction of solar energy. As a precaution against heat transfer through the P.V.C., small joints of a clear flexible plastic that is resistant to heating, were inserted into the poles every two metres. These joints also introduced some flexibility in the poles thereby reducing the possibility of the pole being displaced or broken in a high wind. Small plastic bottles were placed over the lower end of each pole to give the pole a broader base in an effort to reduce any sinkage that may have been caused by either heat conduction through the pole or by the effect of the weight of the pole being concentrated downward on the small cross sectional area. Once these poles were positioned, values for the surface lowering were obtainedby measuring the distance from the surface of the glacier to the top of the pole. In the early stages of field work these measurements were obtained every two or three days but once it was realised that significant surface lowering was normally occurring over shorter time intervals, daily observations were made, except when on three occasions (December 14, 20 and January 13) weather conditions made such observations impractical.

It was necessary to take two measurements at each pole for each observation because of difficulty in determining the actual position of the surface. Indentations, which rapidly developed around each pole and became more prominent through time, and small scale undulations in the surface itself, made it impossible to estimate the position of the surface directly. A length of wood was laid on the surface so that it touched the pole and the surface was assumed to be on the same plane as the underside of the wood. The two measurements obtained at each pole were then meaned to obtain a value from which the daily surface change at that pole could be calculated. The eight values thus obtained from the daily measurements at each pole were in turn meaned to obtain a daily mean value.

Since these values were rounded to the nearest 0.5 cm, any one value can only be within $\pm$ 0.5 cm of its true value, providing all other errors, including that associated with defining the position of the surface are ignored.

B. <u>The Calculation of Water Equivalent Values</u>.

During the study period, values for the surface change were obtained from both a snow and an ice surface. The snow surface that was present at the beginning of the study had ablated by February 8 leaving a surface composed entirely of ice. It is impossible to compare the surface change of a snow and an ice surface from the actual linear values of this change, because in terms of the mass removed or gained, a unit increase or decrease of an ice surface will involve a greater loss of water than a similar change of a snow surface. It is thus necessary to refer the changes occurring in the height of both surfaces to a common base, this being the water equivalent.

Density and surface lowering values are the main variables in the calculation of water equivalent values, but for a snow surface it is also necessary to consider the free water present as this can affect the density value. Free water is not considered in the calculation of water equivalents from the surface lowering of ice because ice has no free water content.

In the present study, values for the density of the snow cover were obtained with the use of a Federal sampler, and from snowpit measurements using a density tube. The calculation of the density through the use of either instrument is the same, involving measuring the mass of snow in a known volume. Both were used because the Federal sampler tends to over-estimate the density due to compaction within the sampler while the density tube tends to under-estimate as ice bands were often not sampled because they did not occur at the pre-determined sampling depths.[3] These differences are due in the main to the manner in which the sample is obtained and its location within the snow cover. The Federal sampler gives an average density with depth, the sampler being inserted vertically into the snow cover, while the density tube values only apply to the precise depth at which they are obtained.

Free water was only determined by actual measurement, for a snow cover which fell shortly after the commencement of this study. (This snow cover is hereafter referred to as 'new' snow). For the snow cover ('old' snow) that was present before this 'new' snow fell, a free water content of 10 percent was used, this value being based on measurements obtained during the previous seasons of study on the Ivory

(3) Pers Com. Dr P. Anderton, N.Z. Ministry of Works, Hydrological Survey

Glacier by the Snow Survey Section. A standard calorimeter method was used to measure the free water content of the 'new' snow.

Although the calculation of density values is straightforward, it is necessary to consider certain characteristics of density when applying these values in the calculation of water equivalent values for the surface lowering of snow. Density changes with respect to both time and space. Such changes being due to compaction by the action of the wind, rainfall, and the weight of the overlying snow. This means that from the time the snow settles until it ablates, or compacts into ice, its density undergoes a change, the rate of this change being rapid in the first few days after falling, and decreasing with time.

Paterson (1969 p. 6) gives a range of snow densities of 0.01-0.03 gcm^{-3} for 'new' snow at low temperatures in calm' to 0.7-0.85 gcm^{-3} for 'very wet snow and firm'. With such a range of densities it is conceivable that within one snow cover, the density could change with depth (due to the difference in time that the snow at various depths has been subjected to compaction) as well as changing with time. It is therefore advisable to sample the density of a snow cover throughout its depth, and at regular time intervals.

In the present study, the following procedures were used to calculate the water equivalent values from the respective values of the density, the surface lowering, and the free water content.

The 'new' snow reached a measured density of 0.4 gcm^{-3} within a day of settling, and this value did not change before this snow was ablated. On the basis of this density the water equivalent values for this 'new' snow were calculated by multiplying the surface lowering values by this density value and correcting for the free water content.

As the density of the 'old' snow was expected to vary with depth, a number of density profiles were obtained over time and space while this snow remained on the glacier. From these profiles a graph of density against depth was constructed. This graph however yielded two curves (relating to the Federal sampler and the density tube) necessitating the plotting of a mean curve between these two. For ease of processing, the ordinate (density) was expressed in terms of water equivalent, with a corresponding scale change obtained by calculating the water equivalent value for one centimetre of surface lowering for various densities and correcting for the free water content the latter being assumed to be constant with time.[5] This gave the graph in fig. 4 from which it was possible to obtain the appropriate water equivalent value for the amount of surface lowering recorded each day.

On the basis of a density[6] of 0.9 gcm^{-3} the water equivalent values for the surface lowering of the ice surface were calculated using the same method as for the 'new' snow with the exception that a free water correction was considered unnecessary, ice being too compact to allow

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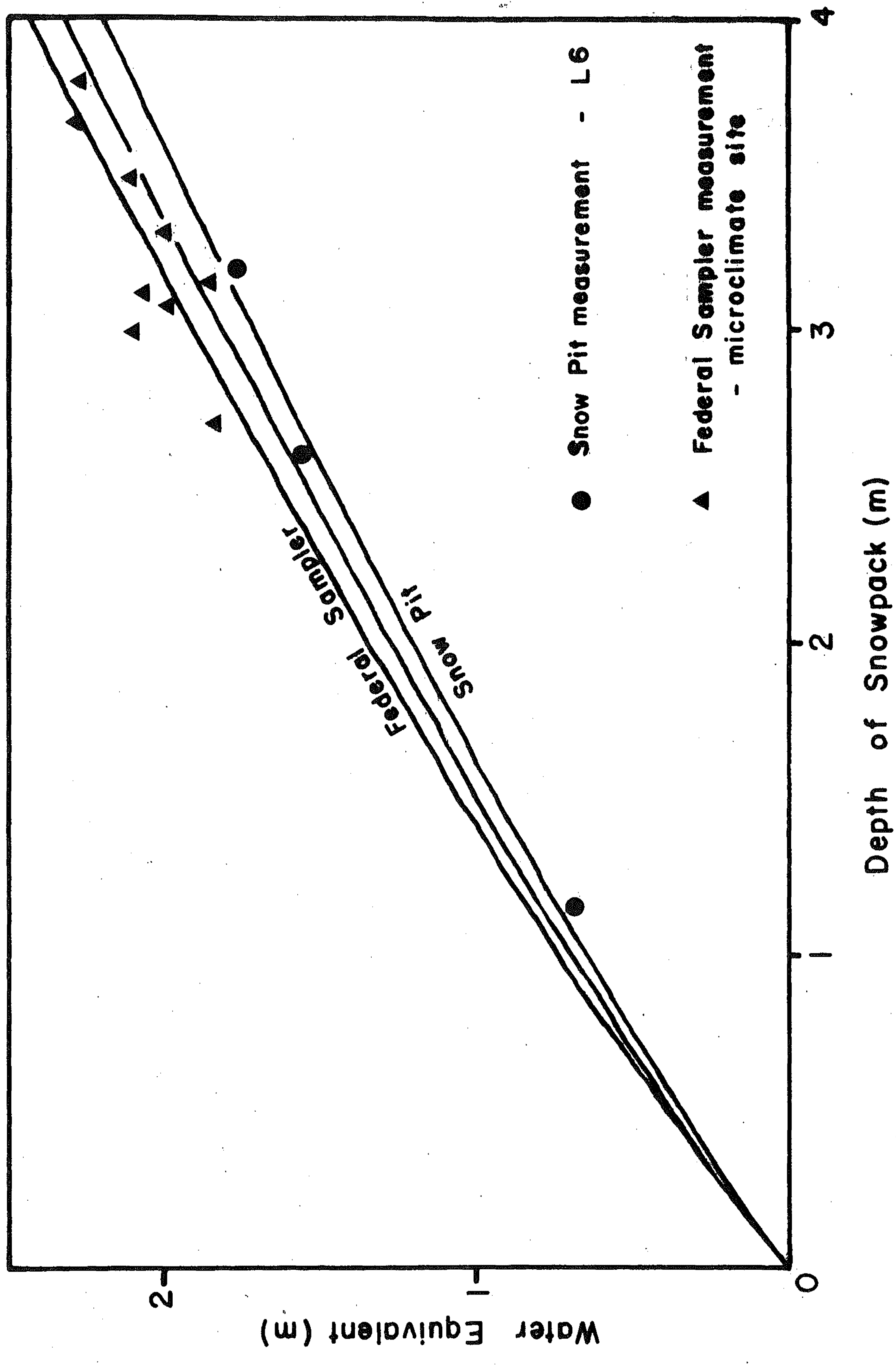
(5) Pers Com. Dr P. Anderton
(6) This density was obtained from measurements undertaken by the snow survey section of the New Zealand Ministry of Works. Pers Com. Dr P. Anderton.

Figure 4: Change of density of snow pack through time.

Figure 4



Snow Pit measurement - L6
Federal Sampler measurement - microclimate site
Federal Sampler
Snow Pit
0
1
2
3
4
Depth of Snowpack (m)
Water Equivalent (m)

free water to be contained within it. Nor was it considered necessary to consider possible changes in the density of the ice as the possible range of densities[7] is only 0.06 gcm^{-3}.

The water equivalent values were calculated using the methods outlined above, for each observation at each pole, and from these, it was possible to obtain mean values for the surface change as shown in table 2:2. It was necessary to use this method to negate possible errors that would have arisen if the original measurements at each pole had been meaned and the water equivalent value for the daily surface lowering calculated from these.

III <u>A description of the Surface Change</u>

a) <u>The Length of the Ablation Period</u>

Qualitative observations showed that surface change was already in progress at the time the field station for this study was established on November 17, 1971, but this change was interrupted between November 23 and November 28 by several snow falls which yielded approximately 53 cm of 'new' snow (see table 2:1). The ablation poles were set in place on November 25 and the first negative surface change measurements were made on November 29, accumulation being recorded between November 25 and 29. Negative surface change continued to be recorded (from November 29) on all days except one (January 10 1972), when accumulations of between 1 and 3 cm were measured at the ablation poles, and was still proceeding when the study period was terminated on February 14 1972.

(7) Paterson 1969 (p. 6) gives a range of densities for ice of between 0.85-0.91 gcm^{-3}.

TABLE 2 : 2

SURFACE CHANGE VALUES

Date	Surface Change[1]	Days in Period	Date	Surface Change	Days in Period	Date	Surface Change	Days in Period
1971 Nov.			1972 Jan.			1972 Feb.		
25	Poles established		4	-58.6	15	1	-1.9	1
28	+6.9	3	5	-2.6	1	2	-2.4	1
29	+4.2	1	6	-1.6	1	3	-4.3	1
			7	-2.3	1	4	-2.5	1
			8	-2.5	1	5	-5.4	1
Dec.			9	-1.3	1	6	-4.8	1
1	-6.4	2	10	-5.0	1	7	-2.2	1
4	-4.9	3	11	-4.3	1	8	-4.3	1
8	-9.0	4	12	-3.6	1	9	-3.7	1
10	-2.6	2	14	-15.6	2	10	-4.8	1
11	-2.1	1	15	-2.3	1	11	-5.9	1
12	-3.4	1	16	-1.5	1	12	-6.4	1
14	-9.1	2	17	-2.6	1	13	-2.2	1
15	-4.4	1	18	-3.7	1	14	-5.5	1
16	-3.9	1	19	-2.4	1			
17	-2.8	1	20	-3.7	1			
18	-3.5	1	21	-5.3	1			
19	-3.5	1	22	-5.9	1			
21	-12.8	2	23	-4.8	1			
			24	-4.0	1			
			25	-3.9	1			
			26	-4.5	1			
			27	-4.8	1			
			28	-5.8	1			
			29	-6.9	1			
			30	+0.8	1			
			31	-2.1	1			

[1] Surface Change in Water Equivalent (cm of water/period).

The values of surface change recorded between November 29 and December 1 cannot necessarily be considered as a mass loss for it is probable that during this time, the 'new' snow mentioned above, was being compacted and this would record as surface lowering while giving no decrease in mass. After December 2 (the date of the first density measurement), the density value for the 'new' snow (0.04 gcm^{-3}) did not alter, suggesting that from this date, compaction was negligable. Compaction was also considered negligable within the 'old snow cover during the time the present study was in progress for no density change was evident between any two density measurements obtained at different times for locations at similar heights above the ice surface. For example, at a height of 50 cm above the ice surface, a density of 0.64 gcm^{-3} was measured on December 10. A similar density, 0.645 gcm^{-3} was obtained for the same height above the ice surface on January 10 and on January 16.

b) Spatial Variations in the Rate of Surface Change

During the period that the surface change was observed (November 29, 1971 to February 14, 1972), there were marked differences in the values obtained at each pole on any one day (see table 2:3). These differences ranged between 0.9 cm water equivalent (w.e.) (January 15) and 5.9 cm (w.e.) (January 10).

The difference between the values for surface change recorded at each pole on any one day could be a reflection of a number of factors, including, incorrect reading and

TABLE 2 : 3

A SAMPLE OF SURFACE CHANGE VALUES[1] AT EACH POLE

Date \ Pole	A	B	C	D	E	F	G	H	Mean of 8 Poles	Range Difference between Poles
1971 Dec.										
15	3.6	4.5	4.5	4.9	4.2	4.8	3.9	5.0	4.4	1.4
16	3.6	3.8	4.7	4.0	4.0	4.2	3.3	3.2	3.9	1.5
17	2.8	2.7	3.3	3.0	3.3	2.5	2.4	2.7	2.8	0.9
18	3.0	3.5	3.2	3.5	3.4	4.0	3.0	4.1	3.5	1.1
19	4.6	3.5	2.8	3.7	2.8	3.4	3.4	3.7	3.5	1.8
1972 Jan.										
5	2.1	1.3	3.6	2.5	2.8	3.8	2.2	2.5	2.6	2.5
6	1.2	0.8	2.3	3.0	1.4	1.7	1.0	1.3	1.6	2.2
7	3.1	1.4	2.3	2.5	2.0	2.3	2.2	2.7	2.3	1.7
8	3.2	2.6	1.6	2.5	2.4	3.0	2.0	2.5	2.5	1.6
9	1.5	1.0	2.3	1.5	1.6	0.4	1.2	2.5	1.3	1.1
10	2.3	5.5	5.9	5.8	5.6	7.2	3.4	4.2	5.0	4.9
23	5.1	6.5	3.2	5.0	3.0	4.8	5.1	6.0	4.8	3.3
24	4.0	5.5	4.1	3.6	3.2	4.0	4.2	3.3	4.0	2.3
25	4.6	5.5	3.2	4.5	1.7	3.9	3.3	4.5	3.9	3.8
26	4.4	4.5	4.5	3.6	5.1	4.5	5.7	3.3	4.5	2.1
Feb.										
9	7.2	2.7	3.2	2.7	4.1	1.8	3.7	4.5	3.7	5.4
10	2.3	7.2	3.6	5.4	5.9	4.1	4.1	5.4	4.8	3.6
11	5.4	5.9	5.9	4.5	5.9	5.4	5.4	9.0	5.9	4.5
12	7.7	1.8	7.2	6.8	7.7	5.9	6.3	7.7	6.4	5.9
13	1.8	3.6	1.8	2.7	2.3	1.4	1.4	2.7	2.2	2.2
14	6.3	4.5	7.2	4.1	8.1	3.6	3.6	6.3	5.5	4.5
Total - 25/11/71 to 14/2/72:	279.3	294.4	294.5	281.4	253.3	282.3	269.2	294.4	476.4	43.2

[1] All values are in water equivalent values (i.e. gcm^{-2}.)

recording of measurements (observer error), a sinkage of one or more poles, errors connected with defining the surface plane and/or an actual spacial variation in the surface change. This last cause could result from spacial differences in the factors causing surface change, but as no attempt was made to measure any spacial variation in the factors causing this change, and as no reference to the possibility of this occurring was found in the papers read, this suggestion can be neither proven or disproven and must therefore remain as a suggestion only.

As the possible error associated with the sinkage of the poles has already been outlined (see p.10) it will not be dealt with here.

On those days where the difference between the poles was large, it was evident that in most cases the magnitude of the difference (see table 2:3) was caused by one observation being either much smaller or larger than the observations obtained at the remaining poles. For example, on February 9 when there was a range of 5.4 cm (w.e.) for the 8 poles, pole A yielded a value of 7.2 cm (w.e.) while at the other 7 poles, the values ranged between 1.8 and 4.5 cm (w.e.). On February 12 when the range for all the poles was 5.9 cm (w.e.), pole B yielded a value of only 1.8 cm (w.e.), much lower than the values recorded at the other poles (these ranging from 5.9 to 7.7 cm (w.e.). If these very high or low values are removed, the range of values for the days on which they occur becomes similar to those (0.9 to 4.0 cm (w.e.)) that occurred on days when no reading is obviously much higher or lower than the rest (e.g. on February 9 the ranges reduces from 5.4 cm (w.e.) to

3.4 cm (w.e.) if the 7.2 cm (w.e.) value recorded at pole A is removed). This would suggest that on days when the range is greater than 4.0 cm (w.e.) the magnitude of the range is due to one value being in error.

An error such as that described in the previous paragraph is most likely due to incorrect observation (i.e. observational error) of the surface change at that pole. However, even if these anomalous values are excluded, it is evident that there is still a difference between the other values. Again the most obvious reason for these differences is an observational error. For example, the method used to define the surface plane could lead to observational error. The most obvious source of error in this case is in the positioning of the wood used to locate the surface plane, for if this wood was placed in a different position each day, at each pole, surface irregularities would cause the observed level of the surface to be located on a slightly different plane or at a height greater or less than it was the previous day. This would cause the measurements at each pole to be based on different reference planes with respect to both the surface location the previous day and its location as compared with that at the other poles and this could cause a difference in the actual measurements obtained at each pole. However, one would expect that observational errors would be random and/or self compensating (B. J. Brinkworth, 1968). That is, one would not expect to find any consistency in the observation of either high or low values, as compared with the daily mean values at any one pole. By adding the deviation from the daily mean of the value recorded at each pole during certain periods, it is evident that at times the observational errors seem to be random and at others they appear to be systematic. For example, for pole H, the total deviation about the daily mean for the period from December 12 to February 10 is zero, but during the last four days (January 11 to 14) the values at each pole are consistently higher than the daily means. At pole B, on the other hand, it is evident that for the period between January 5 and 10 the values at this pole are mainly below the daily mean values. Thus complete randomness is not evident, and from this it could be concluded that the differences between the values recorded at the 8 poles on any one day are not accounted for entirely by observational error. However, some observational error is evident, for if the values obtained at pole A on February 12 (7.7 cm (w.e.)) and 13 (1.8 cm (we.)) are considered, it would appear that there is an apparent compensation between the values obtained on the two days. If the mean value at each of the poles is considered, these being:

Pole A 4.7 cm water equivalent
Pole B 2.7 cm water equivalent
Pole C 4.5 cm water equivalent
Pole D 4.7 cm water equivalent
Pole E 5.0 cm water equivalent
Pole F 3.6 cm water equivalent
Pole G 3.8 cm water equivalent
Pole H 5.2 cm water equivalent

it is found that the mean value at pole A appears to be of the right order of magnitude when compared with the mean values obtained from the remaining poles. This would suggest that compensation by the low value on January 13 for the high value on January 12 has taken place, and this in turn would suggest that the reading obtained on January 12 was in error because of an error in observation.

There is also a tendency for large ranges to be observed on days when the values for surface change are high. For example, between February 9 and 12 high ranges (3.6 to 5.4 cm (w.e.)) were recorded (see Table 2 : 3) on days of relatively high (between 3.7 and 6.4 cm (w.e.) mean daily surface change. On February 13 the mean value dropped to 2.2 cm (w.e.) as did the range of values (2.2 cm (w.e.)). This relationship would also appear to hold for the period January 5 to 10, there being only one day (January 10) with a high range (4.9cm (w.e.)) and high mean value for the surface change (5.0cm (w.e.)). However, it does not hold for the period between December 15 to 19 when high surface change values (e.g.4.4cm (w.e.) on December 14) were associated with a low range (e.g.14 cm (w.e.) on December 17). This situation could be used to reinforce both the argument for observational error and that for a real difference between poles, for it could be argued that the higher the daily values were the greater the chance of making an error in the measurement of them but on the other hand, if there were real spacial differences in the rate of surface change, one would expect these to be more obvious on those days when the magnitudes of the individual readings were greatest.

Thus from the discussion above, it is evident that the observed differences in the values recorded at each pole could be due to either observational error, a sinkage of the poles (discussed on page 10) or a real difference in the rate of surface change, but is most likely due to a combination of all three.

c) Temporal Variations in the rate of Surface Change

The mean daily values for the rate of surface change (in water equivalent) were plotted against time to give the curve shown in Fig. 5. Water equivalent values were used in this section because they enable comparisons to be made between days or time periods without becoming involved with considerations of the surface material.

The daily rates of surface change recorded (see table 2:2), show a considerable range in magnitude from a minimum rate of 1.3 cm (w.e.) to a maximum of 7.8 cm (w.e.). However, from Figure 5, it is evident that for short periods of time, consisting of between 2 and 9 days, the surface change rate remains relatively constant giving periods when the slope of the curve is uniform. For example, between January 5 and 9, the daily rates of surface change differ by only 1.3 cm water equivalent day^{-1} giving an almost constant slope to the curve. The rates of surface change, associated with these periods of uniform slope tend to increase with time, to a period when the rate reaches a value of over 6.0 cm (w.e.) day^{-1}, and then decreased suddenly, to a rate below 3.0 cm (w.e.) day^{-1}, suggesting that the rates of surface change progress through a cycle. For example, between January 5 and 14, the slope of the curve in Fig. 5 increases in three stages, corresponding to mean daily rates of surface change of 2.1, 4.5 and 7.8 cm (w.e.) day^{-1} while between January 15 and 17, the rate drops to 2.1 cm (w.e.) day^{-1} to finally begin a new cycle

Figure 5: The surface change during the Study Period.

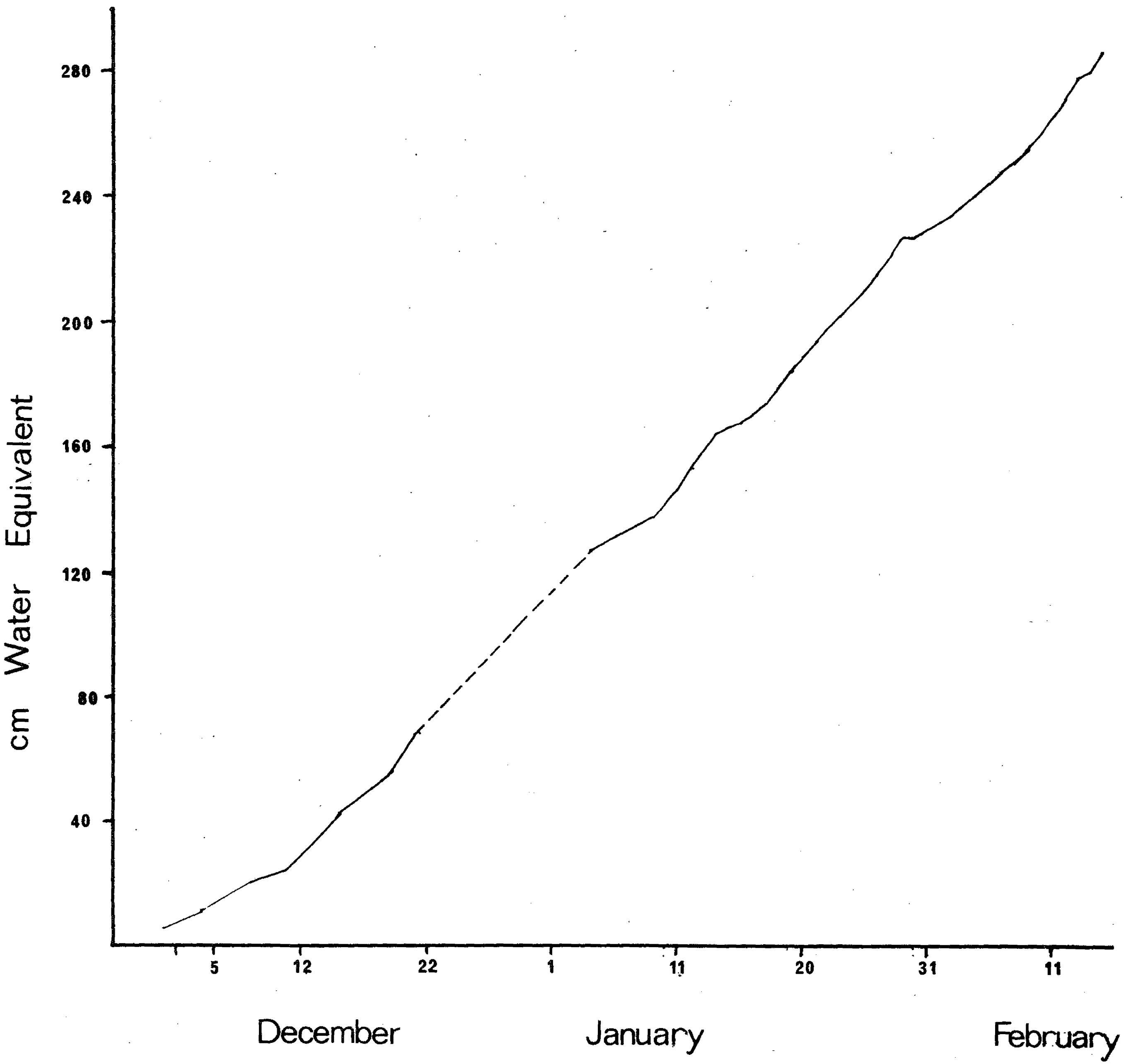

cm Water Equivalent
280
240
200
160
120
80
40
5
12
22
1
11
20
31
11
December
January
February

Figure 5

similar to that between January 5 and 14. There are in fact five such cycles, these being from November 29 to December 21, January 5 to 14, January 15 to 29, January 30 to February 6 and February 7 to 14. In only one of these, between January 15 and 29, is the general pattern of increasing rates of surface change interrupted, this occurring between January 23 and 27 when the rate of surface change decreased from 5.6 cm (w.e.) day^{-1} to 4.5 cm (w.e.) day^{-1} before the general upwards trend of the pattern was resumed between January 28 and 29.

Since the time the first studies were undertaken in the field of glaciology, it has been recognised that the single most important controlling factor for any glacier is the weather (Wallén 1948) in the vicinity of the glacier. For this reason, in the present study an attempt has been made to discover any local or synoptic scale weather pattern or parameter that could be associated with a particular mean daily rate of surface change. To facilitate this comparison, the curve in Fig. 5 was subdivided into time periods within which the rate of surface change (i.e. the slope of the curve) remained constant, and these periods were in turn categorized according to the rate of surface change associated with each period. Five categories were obtained and these are given together with the periods that fall within each, in table 2:4. The following local weather elements associated with each period were evaluated: pressure (Mb), cloud cover (c), rainfall (P.P.T.), wind speed (u), wind direction (ud), temperature (t), relative humidity (wv), and incomming Solar radiation(Si).

TABLE 2 : 4

THE CATEGORIES AND PERIODS OF SURFACE CHANGE RATES

Categories	Periods	Dates	Rate of Surface Change (cm Water Equivalent/Day)
1. Below 3.0 cm/Day	a.	Nov.30 - Dec.11	2.3
	b.	Jan. 5 - Jan. 9	2.1
	c.	Jan.15 - Jan.17	2.1
	d.	Jan.31 - Feb. 2	2.1
	e.	Feb. 7	2.2
	f.	Feb.13	2.2
2. 3.1 - 4.0 cm/Day	a.	Dec.12 - Dec.19	3.8
	b.	Jan.18 - Jan.20	3.3
	c.	Feb. 3 - Feb. 4	3.4
3. 4.1 - 5.0 cm/Day	a.	Jan.10 - Jan.12	4.3
	b.	Jan.23 - Jan 27	4.5
	c.	Feb. 8 - Feb.10	4.3
4. 5.1 - 6.0 cm/Day	a.	Jan.21 - Jan.22	5.6
	b.	Feb. 5 - Feb. 6	5.1
5. Above 6.1	a.	Dec.20 - Dec.21	6.4
	b.	Jan.13 - Jan.14	7.8
	c.	Jan.28 - Jan.29	6.4
	d.	Feb.11 - Feb.12	6.2

Data for the periods prior to January 5 have not been included because of insufficient climatological data.

Average values for each weather element within each period were calculated and are given in table 2:5. However, the picture obtained from table 2:5 is one of confusion, making it difficult to extract any pattern that might relate a particular weather pattern or element to any one rate of surface change. Therefore, the average values of each element for each category were calculated and these are presented in table 2:6.

Since periods 1e and 1f were only of 1 day duration each and as they appear to be anomolously located in category 1, having high temperatures and other indications of misplacement (e.g. high pressure and short-wave radiation values), they were excluded from the calculation of the average values within each category. The only apparent reason for their being located in category 1 is a probable observer error in measuring the rate of surface change on the two days.

From the values given in table 2:6, a more distinguishable pattern emerges in relation to the variation of each of the parameters between each category. Pressure, temperature, short-wave radiation income and, to a more minor degree, wind speed, all tend to increase as the rate of surface change increases whereas rainfall, humidity and cloud cover tend to decrease and the wind direction remains relatively constant. However, in a number of cases these trends are interrupted or reversed in one or another category (excluding category 5 for the moment). For example, in category 3 the pressure decreases and the

TABLE 2 : 5

THE AVERAGE VALUES FOR EACH WEATHER ELEMENT FOR EACH PERIOD[1] OF SURFACE CHANGE

Category	Period	Pressure (mb)	Cloud Cover ($\frac{1}{8}$'s)	Daily Average Rainfall (mm)	Wind Speed (m/sec)	Wind Direction	Temp. (°C)	Relative Humidity (%)	Short-Wave Incoming Radiation (Ly/Day)	Rate of Surface Change (cm Water Equivalent/Day)
1	b	846.2	6	4.7	1.63	N	3.3	79	457	2.1
	c	849.2	7	1.8	1.24	N	3.0	91	344	2.1
	d	845.3	5	13.1	3.30	SE	2.3	76	392	2.1
	e	864.0	4	0.0	2.17	NNW	6.0	83	501	2.2
	f	861.9	1	0.0	3.00	N	7.2	53	552	2.2
2	b	851.8	8	2.8	2.25	NE	4.5	93	273	3.3
	c	857.6	4	0.0	1.95	N	5.8	76	499	3.4
3	a	851.3	6	5.7	1.77	N	5.0	91	377	4.3
	b	853.8	5	0.7	2.24	N	5.8	85	478	4.5
	c	854.0	4	2.5	2.64	N	5.3	67	551	4.3
4	a	852.8	5	0.0	2.54	NE	7.1	66	556	5.6
	b	865.2	4	0.0	2.11	SE	6.2	76	540	5.1
5	b	843.2	8	82.5	12.30	SE	2.7	96	212	7.8
	c	847.3	7	148.3	4.23	SE	3.9	90	254	6.4
	d	859.1	5	1.6	2.10	N	7.1	85	400	6.2

[1] These periods are given in Table 2 : 4.

TABLE 2 : 6

THE AVERAGE VALUES OF EACH WEATHER ELEMENT FOR EACH CATEGORY [1] OF SURFACE CHANGE

Category	Pressure (mb)	Cloud Cover ($\frac{1}{8}$'s)	Daily Average Rainfall (mm)	Wind Speed (m/sec)	Wind Direction	Temperature (°C)	Relative Humidity (%)	Short-Wave Incoming Radiation (Ly/Day)	Rate of Surface Change (cm Water Equivalent/Day).
1	849.9	6	6.5	2.05	N	2.9	82	397	2.1
2	854.7	6	1.4	2.10	NNE	5.1	84	386	3.3
3	853.0	5	3.0	2.22	N	5.3	81	469	4.4
4	859.0	4.5	0.0	2.28	E	6.7	71	548	5.3
5	849.0	7	77.7	5.54	SE	4.6	90	255	6.8

[1] These categories are given in Table 2 : 4.

rainfall increases relative to their values in category 2 while in category 2 the short-wave radiation income decreases and the humidity increases relative to category 1. It is interesting to note that while there are these fluctuations in the trends between categories, the overall result is an increase in the rate of surface change, suggesting a complex inter-relationship between the variables responsible for any one rate of surface change.

In category 5 there is a reversal in the trends associated with all the parameters except wind speed, which could suggest that the wind speed parameter is of major importance in the rate of surface change recorded on any one day. However, it could also suggest merely a change in importance between the variables, a situation that is also evident in all other categories and which re-emphasises the possibility of a complex relationship between the parameters.

The values presented in table 2:5 for each separate period within each category show even greater variation and complexity. The apparent trends that are evident in table 2:6 are not evident in table 2:5 with the possible exception of the temperature, which still shows a tendency to increase with increasing rates of surface change. If humidity is considered with temperature (table 2:5), a further trend is recognisable, for it is evident that progressively higher values of temperature combined with constant humidity values, gives an increase in the rate of surface change (see Periods 2C and 4B), while an increase in humidity with constant temperature values, also gives an increase in the rate of surface change (see Periods 2C and 3B). This suggests yet again a complex inter-relationship between the parameters. In fact, only in category 5 does it appear that the rate of surface change may be attributable in a large part, to only one parameter. With reference to table 2:5, it is evident that the rainfall values recorded in periods 5B and 5C are of a much greater magnitude than values for the same parameters recorded in any other period and, as the remaining parameters in these two periods would tend to indicate a lower rate of surface change than that actually measured, it is reasonable to suggest that the magnitude of the rainfall during these two periods was responsible for a large part of the surface change recorded. The effect of the rainfall can be viewed from two view points; these being an added heat input causing more melting (this will be dealt with in Chapter 3) or an erosional effect induced by the action of the rainfall striking the snow or ice surface. While the snow cover remained, rainfall could cause compaction of this snow by the very mechanics of the surface being bombarded with raindrops falling at a considerable velocity. However, compaction of the order needed to explain the surface change values recorded during times of intense rainfall would cause a density change in the snow pack and this was not evident from the density measurements undertaken. Once the snow had ablated it was noted that the thin crust of granular ice that was evident on the surface of the glacier before a storm was not evident after the storm, suggesting that its removal was probably associated with the rainfall, and, as during storms small pieces of ice were observed in the water contained in the melt water channels in the glacier, it could be concluded that this ice was removed by the impact of raindrops. However, it is difficult to imagine erosion by rain removing any more than this top crust of granular material, but it is nevertheless important to realise that not all of the high rate of surface change observed in Period 5C and D need necessarily be attributed to processes of melting, evaporation or sublimation.

An indistinguishable pattern of weather at the Synoptic scale existed during the period of study, although there was a tendency to have high rates of surface change (category 5) associated with periods when the Ivory Glacier was influenced by low pressure systems. For example, deep depressions on January 13 and 14 and January 28 and 29, coincided with high rates of surface change (7.8 and 6.4 cm respectively). The depressions brought high winds (4.3 to 12.3 m sec^{-1}) and intense short period rainfalls (82.5 to 148.0mm day^{-1}) to the Ivory Glacier, and it could be suggested from this that the rates of surface change during these two periods were the result of these two factors (wind and rain), a suggestion already mentioned in connection with rainfall.

It must be concluded from the discussion in this section that no one element or recognisable combination of elements can be used to account for any one rate of surface change, for the trends that are apparent at one level of consideration (average category values) are not evident at the next lowest level of consideration (average period values) suggesting a complex inter-relationship that could only be discovered by intensive statistical analysis or by considering these factors in relation to their heat input rather than the actual value of the units in which they were measured.

IV Summary

In the present chapter, an attempt has been made to describe the methods used, the problems encountered and the results obtained from the attempt to measure the surface change at the Ivory Glacier. The methods used were in the main, the conventional methods used in any glacial mass or energy balance study. The problems too were mainly those encountered by other investigators (see Ørvig and Stanley 1969) with the exception that the water that filled the holes that were drilled into the ice did not appear to refreeze.

The results obtained have been considered both as to the spacial variation between poles on any one day, and the temperal variation, and an attempt has been made to find some reason for these variations. It is evident from the discussion presented above that both the spacial and temperal variations can be explained in part but a qualitative description and analysis is not sufficient to explain all the variations, which would suggest that the processes must be considered in terms of the energy that is available for their functioning and this will be dealt with in Chapter 3.

CHAPTER

3

The Energy Balance

I Introduction

The values for the surface change discussed in the previous chapter indicate a large loss of mass from the surface of the Ivory Glacier. A loss of such a magnitude would suggest that considerable amounts of heat energy must have been available at the surface of the glacier for the processes of ablation. In the present chapter this heat energy is discussed in terms of the type, magnitude and relative importance of the relevant energy sources at the surface (these sources being, net radiation, sensible heat and latent heat). Consideration will also be given to the heat content of the precipitation and the importance of this source of energy.

Only the period between January 5 and February 14 has been considered for the discussion below since lack of data in the remaining period (November 18 to December 21) made the calculation of the relevant heat fluxes impractical

The daily values given in this chapter refer to the 24 hours between 1500 hours and 1500 hours.

II Radiation

The net flux of radiation at the surface of the glacier may be expressed by

$$R = S_1 (1 - \alpha) - L \quad (1).$$

where

R is the net radiative flux

S_1 is the incoming short-wave radiation

α is the albedo

L is the net long-wave radiation.

In the present study the net radiative flux, the incoming short-wave radiation and the albedo were measured directly. Measurement of the net long-wave radiation was neglected because of lack of instrumentation and because it is encompassed within the net radiation term. Incoming short-wave radiation was measured, although it, too, is included within the net radiation term because it is usually the major source of incoming radiation.

A C.S.I.R.O. Net Radiometer, Model CN2 (manufactured by Middleton and Company Pty. Ltd., Australia) was used to measure the net radiation (see Plate 3). Integrated values of both positive and negative net radiation being obtained for 3 hourly periods between 0600 and 1800 and for the 12 hours between 1800 and 0600.

The incoming short-wave radiation was obtained from a Rimco C.S.I.R.O. silicon solar cell radiation integrator (manufactured by Rauchfuss Instruments and Staff Pty. Ltd., Australia) attached to a summer long-term recorder (see Plate 4), the frequency of observation being the same as for the net radiation. Two instantaneous readings using a potentiometer, of a model CN8 albedometer (see Plate 5), (manufactured by Middleton and Company Pty. Ltd., Australia) faced first upwards and then downwards were used to calculate the albedo. Observations for this parameter were taken under most cloud cover conditions and at varying times during the day.

Plate 3

The Net Radiometer inside Kea protection cage 1.

1. This shield was found to cast a shadow over the sensor for up to an hour per day, thus from January 5 the sensor was placed outside this cage by attaching it along one of the sides at the top so that it protruded from point A.

Plate 4

The Short-wave Radiation Sensor and recorder and STEVENSONS screen

1. The Sensor

2. The Recorder

3. STEVENSONS Screen - containing maximum and minimum thermometers and air temperature sensor which is also attached to 2.


A

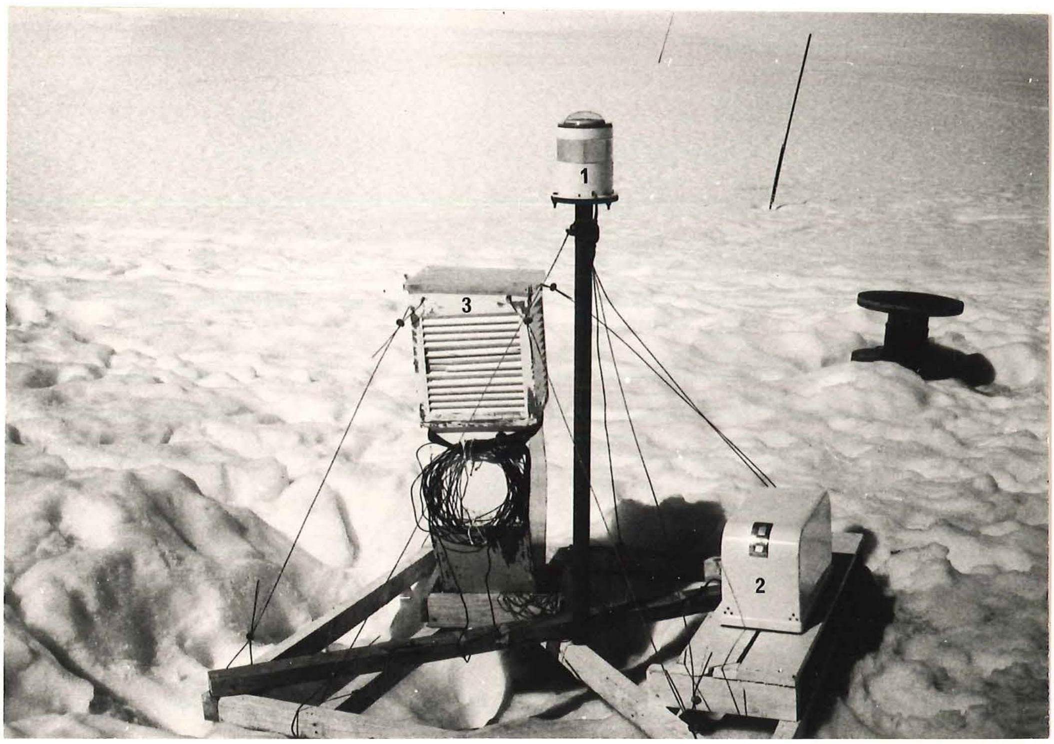

1
3
2

Plate 5

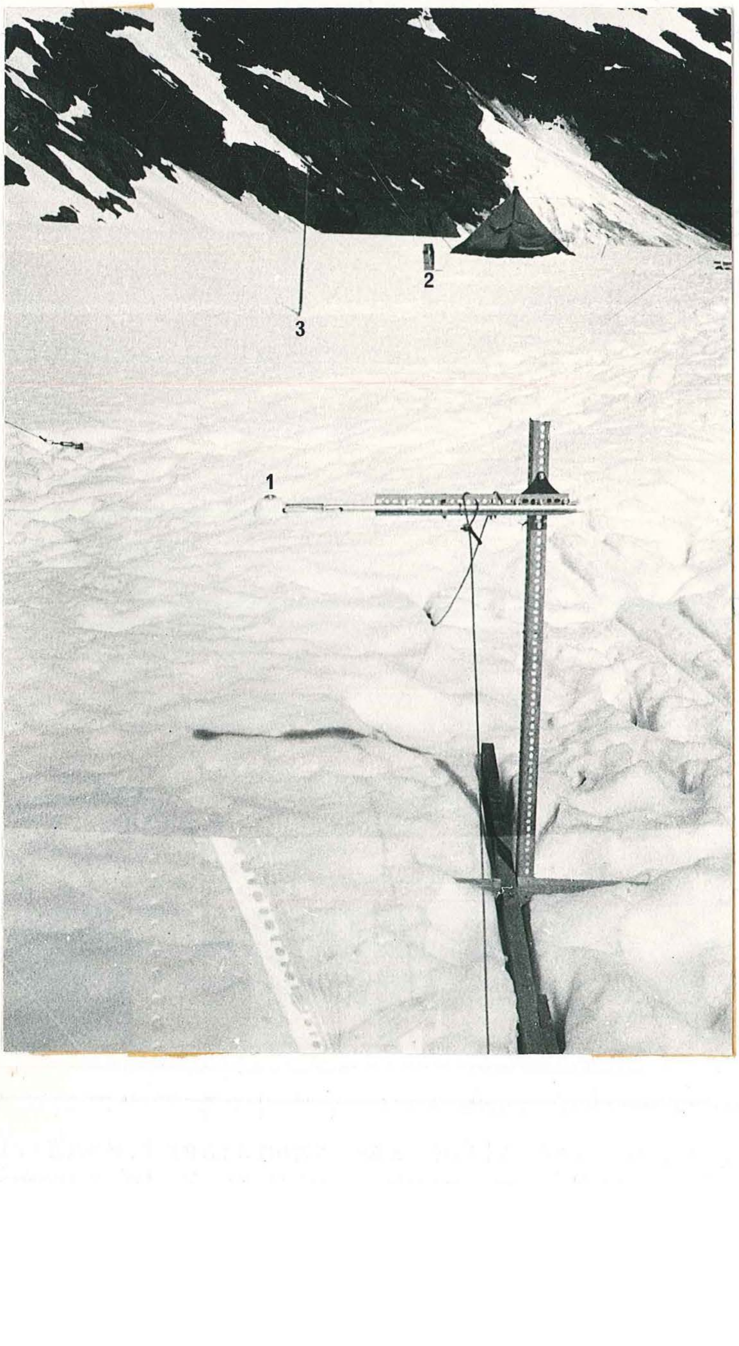
The albedometer with the sensor facing down.

Key:

1) Albedometer

2) 'Cassella' recording Raingauge

3) An ablation pole


3
2
1

No one of the instruments was calibrated before departure to the field, the sensitivities given by the manufacturers being taken as accurate. However, when calibrations were carried out, it was found that these sensitivities were in error and these errors were corrected in the calculations.(1) No correction was necessary for the albedo readings since these were obtained by calculating the ratio of the instantaneous values of the outgoing short-wave radiation to the incoming short-wave radiation, and this ratio would not be expected to be influenced by an incorrect instrument sensitivity, as this would affect both in a similar manner.

A) Short-Wave Radiation

The daily value for short wave radiation income ranged, for the period between 0600 and 1800 hours, from 0.054 ly min^{-1} (between 1200 and 1500 hours on January 19) to 1.72 ly min^{-1} (between 1200 and 1500 hours on February 11). At night (between 1800 and 0600 hours) the incoming short-wave radiation could be considered negligible as it reached a maximum value of 0.067 ly min^{-1} (49.8 ly for the period) only once and had an

---

(1) Each instrument was calibrated against a similar instrument at a similar exposure. The corrections applied to the values (x) obtained in the field were as follows:
(a) for the incoming Solar Radiation - 0.913.
(b) for the net Radiation (R).
(i) 0.045 x when R was + ve.
(ii) 0.968 x when R was -ve.

average value of 0.01 ly min^{-1} (7.2 ly for the period). The daily short-wave radiation is shown graphically in fig. 6.

It has been found by other workers in this field such as Sagar (1966), and Orvig (1954), that the solar radiation income at the surface of the glacier was dependent to a large degree on the cloud cover. Table 3 : 1(2) gives some values for solar radiation income on days with clear and overcast skies. Taking into account the fact that the total short-wave radiation income at the top of the atmosphere at any one latitude varies through the year, it is evident from Table 3 : 1 that in general the values under overcast conditions are considerably less than those under clear sky conditions. In fact, reductions of between 18 and 74% are evident from this table. However, the values for these reductions have a much larger range than those given by other authors, (e.g. Sagar 1966 (p.40) reports reductions of between 30-40 per cent) and thus the actual magnitude of the reduction must remain in doubt. Cloudiness (i.e. cloud amount and thickness), however, is only one factor which might affect the solar radiation

---

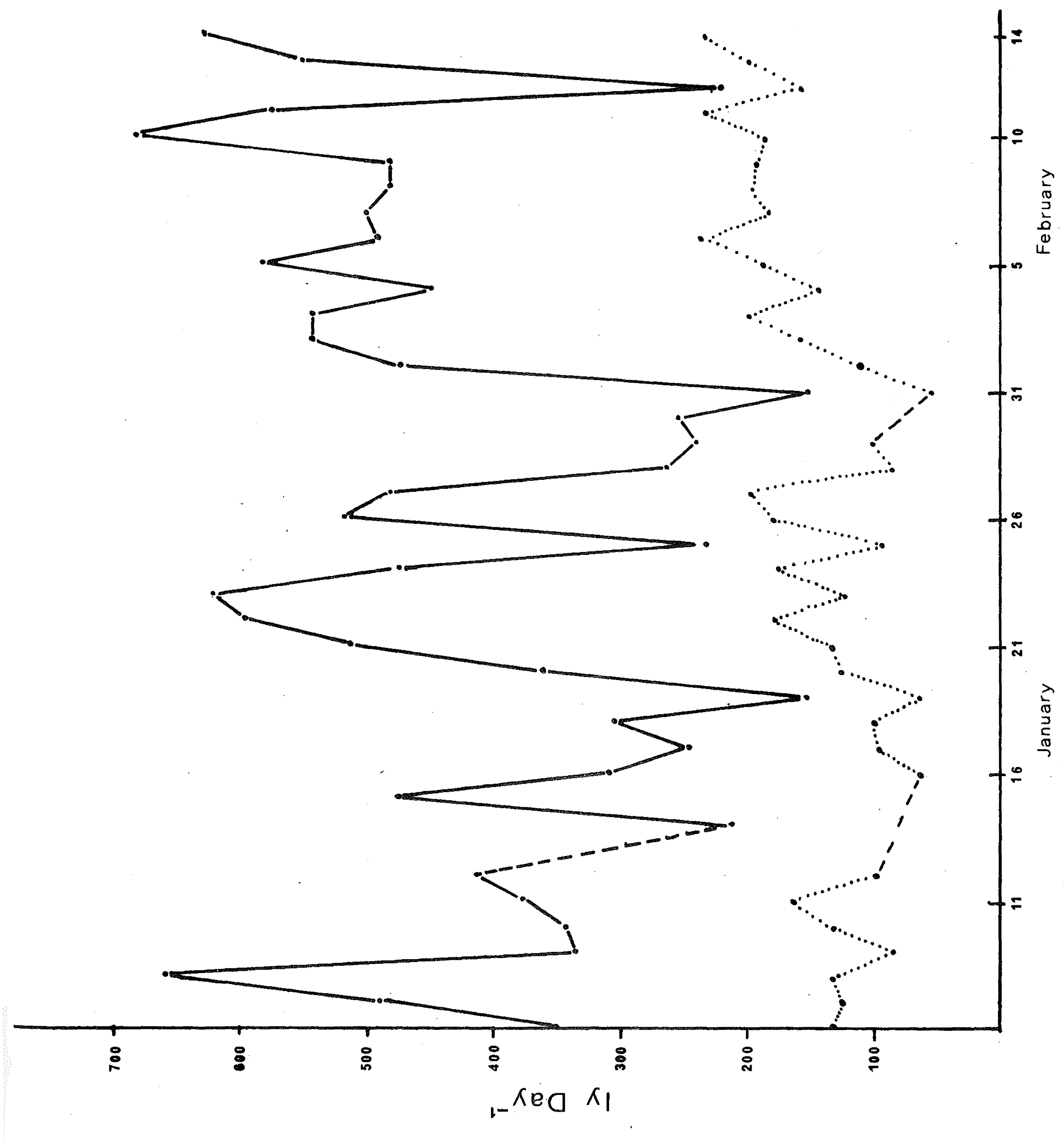
(2) For this table to be valid it was necessary to correct the daily totals of short-wave radiation income to account for the variation with the time of year of the total short-wave radiation incident on a flat plane at the top of the atmosphere. This was done by reference to the Smithsonian Meteorological tables (1966 p.418).

Figure 6: Daily total incoming short-wave Radiation and Net Radiation

____ Short-wave Radiation

..... Net Radiation

Figure 6



700
600
500
400
300
200
100
ly Day^{-1}
11
16
21
26
31
5
10
14
January
February

TABLE 3 : 1

INCOMING SHORT-WAVE RADIATION
UNDER CLEAR AND OVERCAST SKIES

Date	Radiation Clear Sky (ly)	Date	Radiation Overcast Sky (ly)	Date	Overcast/ Clear
1972		1972		1972	
Jan.		Jan.		Jan.	
12	412	10	341	10/12	0.82
23	623	25	237	23/25	0.38
27	482	31	175	27/31	0.36

income for water vapour in the atmosphere, the mass of the atmosphere itself, and the angle of incidence are all of importance.

Occasionally during times of partial cloud cover accompanied by bright sunshine, it was found that high short-wave radiation income was observed. For example, on February 11 between 1200 and 1500 hours, a figure of 1.72 ly min^{-1} was recorded during conditions of rapidly changing cloud cover (the average cloud cover for the period being 4/8) while figures of 1.4 ly min^{-1} and 1.12 ly min^{-1} were recorded for similar time periods under clear sky conditions on February 7 and 13 respectively. These figures were also corrected for variations in the incident short-wave radiation at the top of the atmosphere. It has been suggested that this phenomenon may arise from a situation of multiple reflection of the solar radiation (Wallen, 1948).

It was also evident from visual observations in the field that on overcast days, the density of the cloud cover affected the short-wave radiation income (for examples see table 3 : 2) to the extent that the value of the short-wave radiation income (corrected for differing extra-terrestrial intensity for the same time of day at difference times of the year) could be reduced by as much as 60 - 70%.

B) Albedo

The albedo values were calculated from the equation

$$\alpha = \frac{So}{Si} \times \frac{100}{1} \qquad (2)$$

TABLE 3 : 2

AVERAGE SHORT-WAVE RADIATION INCOME ($ly\ min^{-1}$) FOR DIFFERENT OBSERVED DENSITIES[1] OF CLOUD AT DIFFERENT TIMES OF DAY [2]. UNDER COMPLETE CLOUD COVER

Time	No. of Obs.	Slightly Dense	No. of Obs.	Moderately Dense	No. of Obs.	Very Dense
0900	7	0.63	10	0.46	4	0.35
1200	8	0.94	7	0.59	15	0.46
1500	4	0.97	12	0.87	15	0.47
1800	3	0.57	8	0.62	10	0.17

1. The density was qualitatively grouped into the three categories given in this table on the basis of the base height of the cloud, and a subjective assessment gained from a light meter of the light conditions :-

   These were catagorized as follows -

   (a) Slightly Dense - cloud height, above 2000m above sea level - light meter reading from 16 to 20 units.

   (b) Moderately Dense - cloud height, 1500-2000m above sea level - light meter reading from 11 to 15 units.

   (c) Very Dense - cloud height, below 1500m above sea level - light meter reading from 0 - 10 units.

2. The densities and short-wave radiation were obtained over ten-minute periods at the hours given.

where

α is the albedo - expressed as a percentage.

Si is the incoming short-wave radiation.

So is the outgoing short-wave radiation.

The average albedo for the period when the surface at the measuring site was composed of snow (January 5 to 25) was 71%. However, the individual values within this period showed a wide range, from 94% (recorded at 1400 hours on January 16) to 53% (recorded at 100 hours on January 23). This range is larger than that recorded by some investigators (e.g. Lougeay (1969) - range 68.4 - 90.7%), however, Wallen (1948) presents data which indicates that a wide range of albedo values over snow have been found by many investigators, but usually an average value in the vicinity of 60-65% has been obtained over snow conditions similar to those encountered on the Ivory (i.e. wet snow conditions). This would tend to indicate that the value obtained for the Ivory is somewhat high. As this figure 71% was obtained from readings taken under most weather conditions, there is a distinct possibility that error may be present, but from the values obtained under stable cloud cover conditions (range 63 to 76%) it would appear that the figure obtained for all the observations is reasonable. The 71% value was used in further calculations because it was found to be statistically of greater significance than the 69% value mainly because of the number of observations upon which the two values were based.

The mean albedo over the ice surface (from January 26 to February 14) was 48%. The range of values in this instance being from 87% (recorded at 1400 hours on February 12) to 29% (recorded at 1500 hours on February 8). It was found that under clear sky conditions, there was a tendency for the average albedo values to increase as the angle of incidence of the short-wave radiation decreased (see table 3:3). This phenomenon was particularly noticeable during the latter part of the study period when clear skies were more predominant. Wallen (1948) found a similar occurrance over frozen snow and ice but Lougeay (1969) found that the lowest albedo readings were observed just after sunrise and just before sunset. The average value obtained for the albedo of the ice is within the range of values (40%to 50%) that have been used by previous investigators (e.g. Wallen, 1948).

During the observation of albedo, it was noticed that to obtain accurate results the observations needed to be undertaken during stable cloud conditions, for if the cloud cover was fluctuating, error could result (especially with the method used in this study), as in the time that elapsed between the upward and the downward readings the incoming shortwave flux could have changed significantly giving erroneous results. (For example, on three occasions during the present study, albedo values of between 100 and 120% were recorded during fluctuating conditions).

Making use of equation (3), average albedo readings over snow and over ice were used in conjunction with the

TABLE 3 : 3

ALBEDO VALUES (%) OBTAINED AT 3-HOURLY INTERVALS BETWEEN 0600 AND 1800 HOURS FOR THE PERIOD FEBRUARY 8 - FEBRUARY 14.

Date	Time				
1972	0600	0900	1200	1500	1800
Feb. 8	54	42	30	29	42
" 9	60	52	43	46	54
" 10	46	45	36	42	44
" 11	42	44	40	48	54
" 12	41	46	42	62	51
" 13	47	57	39	39	49
" 14	65	43	41	41	50
Average:	49	47	37	44	49

daily totals of short-wave radiation income to calculate the amount of incoming short-wave radiation absorbed at the surface.

$$Sa = Si\ (1-\alpha) \qquad (3)$$

where

Sa is the absorbed short-wave radiation

Si and α have the same meanings as already detained.

The values obtained for the absorbed short-wave radiation are given in table 3:4. From these values, it was calculated that the average daily increment of solar energy was approximately 180 ly day^{-1}.

C) Net Radiative flux

Although the daily totals of net radiation obtained from the measured values were found to be positive on all the days of the study period (see fig. 6), periods of negative net radiation were recorded. The highest absolute values (e.g. -64.8 ly 12 hrs^{-1}) for this negative net radiative flux, were, not surprisingly, recorded between 1800 and 0600 hours during periods of light or zero cloud cover, however, these values were never of a large enough magnitude to register the daily values as negative. During other periods (e.g. 0600 to 0900 hours on January 21) small negative net radiation values were observed but these were of a lower order of magnitude (e.g. 4.6 1y 3h^{-1}) and had negligible effects on the daily totals. The total radiative flux for the period from January 5 to February 14 was calculated as being 5.371 K ly which gives an average of 148 ly day^{-1} radiant energy input to the surface.

The values for the net radiation and absorbed short-wave

TABLE 3 : 4

DAILY TOTALS OF INCOMING SHORT-WAVE RADIATION (Si), ABSORBED SHORT-WAVE RADIATION (Sa), NET ALL-WAVE RADIATION (R) AND NET LONG-WAVE RADIATION (L).

UNITS IN ly DAY $^{-1}$

January 1972					February 1972				
Date	L	Si	Sa	R	Date	L	Si	Sa	R
6	33	342	99	132	1	-134	477	248	114
7	-17	489	142	125	2	-125	546	284	161
8	-58	660	191	133	3	-85	546	284	199
9	-12	336	97	85	4	-89	451	234	145
10	34	344	99	133	5	-105	585	304	191
11	55	376	109	164	6	-18	495	257	239
12	-21	412	119	98	7	-70	501	261	191
14	-	212	62	-	8	-60	484	251	191
15	-	476	138	-	9	-56	484	251	195
16	-24	310	90	66	10	-167	686	356	189
18	12	306	89	101	11	-65	579	301	236
19	20	152	44	64	12	46	221	115	161
20	23	362	105	128	13	-87	552	287	200
21	-12	514	149	137	14	-91	630	328	237
22	9	598	173	182					
23	-57	622	180	123					
24	39	476	138	177					
25	32	234	68	96					
26	-88	520	270	182					
27	-52	482	251	199					
28	-57	266	138	81					
29	-24	242	126	102					
31	-21	153	79	58					

radiation when compared with the aid of the equation for the net radiative flux, shows that there must be an additional sink or source of radiative energy for the two sides of the net radiative flux equation to be equal. By re-arranging the net radiative flux equation, it is possible to show that this additional factor is the flux of net long way radiation thus:

$R = Si\ (1 - \alpha) - L$

by re-arrangement, gives

$L = Si\ (1 - \alpha) - R$ (4) Sagar (1966 p. 42)

From equation (4), it is possible to obtain a value for the net long-wave radiative component, but not possible to distinguish between its incoming and outgoing components. It was stated earlier (see page 37) that the net long-wave component of the radiative flux was not measured, for it was considered to be of little importance in the present study. However, the values for this component, given in table 3:4, do not confirm this assumption for on many occasions, they account for a considerable sink or source of energy (e.g. on February 10 a value of -167 ly day^{-1}, 46.5% of the absorbed short-wave radiation, was calculated for the net long-wave radiation). The range of the net long-wave radiation figures of 165 ly day^{-1} to 46 ly day^{-1} would tend to confirm the suggestion that this parameter's contribution to the net radiation values was significant especially as the value of the net long-wave radiation can be up to 46.5% of the absorbed short-wave radiation.

III <u>The latent and Sensible Heat Fluxes</u>

For sensible or latent heat to reach the earth's surface or be transferred from that surface, it must undergo two types of transfer process, these being molecular and turbulent transfer. Molecular transfer only takes place within a few millimeters of the surface for turbulence by the physical law cannot reach the surface (Sellers 1965 p. 142). To guage the flux of sensible and latent heat at the surface, it should theoretically be possible to just measure the temperature, humidity and horizontal wind gradient within the laminar boundary layer(3) where molecular transfer occurs but as this layer is so ill-defined, this is a difficult if not impossible task. However, if one assumes that the vertical fluxes of sensible and latent heat are similar at the surface and 1 meter above the surface(4) and also assumes that the turbulent transfer is equal to the molecular transfer over this height(5), it is then possible to measure the respective components of these fluxes below 1m to ascertain the resultant fluxes at the surface.

There are three main methods that have been used to obtain the sensible and latent heat fluxes. These are the eddy correlation method, the energy balance method and the aerodynamic method. A discussion of the relative merits

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(3) Sellers, 1965 p. 141 says of the laminar boundary layer, 'a layer of air, at most a few millimeters thick, and usually much less than that, adheres with great tenacity to the surface! Within this layer, heat, matter (water vapour) and momentum are transferred vertically only by molecular process,....'

(4) '...the vertical flux of sensible heat is virtually the same at 1 meter as it is at the surface. The same is true of the vertical flux of water vapour or momentum...' (Sellers, 1965 p. 142)

(5) Ibid p. 143.

of all three may be found in Sellers (1965) Chapter 10.

For this study, the aerodynamics method was used to calculate the sensible heat flux, the latent heat flux being evaluated by the use of the Bowen Ratio. The aerodynamic equation for the flux of sensible heat is:

$$H = \frac{\rho Cp \cdot K^2 \cdot U_z \cdot (T_z - T_o)}{(\ln \frac{z}{z_o})^2} \qquad (5)$$

(Lougeay 1969 p.92)

where -

ρ is the density of the air at constant pressure

Cp is the specific heat of dry air at constant pressure

K is Von Karman's constant (Saggar, 1965 p. 47 gives a value of 0.4 for this as do Wallen, 1948, Hubley, 1955 and others).

U_2 is the wind speed at height z

T_2 is the temperature at height z

To is the temperture of the surface

$\ln \frac{z}{z_o}$ is the natural logarithm base $_e$ of the ratio of the height (z) to the roughness length (zo). The derivation of this equation may be found in Appendix 1.

As values for the density and the specific heat of air may be found from tables (e.g. the Smithsonian Meteorological Tables 1966), to evaluate the equation, only the wind speed and the temperature need be measured. z_o may be obtained from the measured wind profiles by either directly reading its value from plots of the wind speed against the log of the height (i.e. it can be evaluated by finding where the wind profile intercepts the ordinate) or by calculation using the equation:

$$\log z_0 = \frac{(U_2 \cdot \log z_1 - U_1 \cdot \log z_2)}{U_2 - U_1} \qquad (6)$$

Where U_2 and U_1 are wind speeds at heights z_2 and z_1.

The aerodynamic approach is based on the assumption of a logarithmic profile of wind speed, temperature and humidity in the first metre above the surface. However, this assumption is only significant if near neutral stability conditions exist in this layer. Under neutral stability conditions, the co-efficients of eddy transfer of heat (K_h), water vapour (K_v), and momentum (K_m) can be considered equal (Sellers, 1965).

As K_h and K_v are difficult to assess, it is possible to substitute for K_m using:

$$K_m = \frac{U_z \, K^2 \, z}{\ln \frac{z}{z_o}} \qquad (7)$$

into the respective equations for the latent and sensible heat fluxes.

Before any further discussion can be undertaken on the sensible and latent heat fluxes, it is necessary to consider the variables used to calculate them.

A. Wind Speed

Values for the wind speed were obtained from an Ota Keiki anemometer ('large') and integrator, the anemometer was located 2.8 metres above the surface on a steel mast. Totals of wind run were recorded every three hours between 0600 and 1800 hours and 10 minute wind runs were obtained at the same time as the 3 hourly observations were made.

Whenever conditions were favourable, the wind profile was measured at six levels[6] (see Plate 6) by miniature Rimco anemometers connected to an integrating unit. 149 such profiles were obtained relating to wind runs of between ten and twenty minutes each. These profile studies could only be undertaken in fine conditions as the sensitivity of the anemometers was such that any moisture settling on them would have led to erroneous results.

Of the 149 profiles obtained, only 46 were considered as acceptable for use in further calculations, as they were the only ones to register logarithmic profiles. The rest did not show this logarithmic nature because, either the wind at the time of recording may not have been logarithmic or because of the instrument malfunctioning.

The mean wind speed at the 2.8 metre level is given in fig. 7. From this, it is evident that except for isolated days, the mean wind speed was low being within a range of between 0.79 m sec^{-1} and 3.75 m sec^{-1}. This is emphasised by the mean wind speed for the period between January 5 and February 14 (excluding January 13, 14 and 15 when no records were obtained at the instrument site) being only 2.33 m sec^{-1}. However, this mean wind speed masks the variation that did occur in the wind speed. A maximum measured value of 10.8 m sec^{-1} was obtained on January 28 from a ten minute wind run at 1200 hours. However, this was not the highest wind speed experienced for on January 13, 14, and 15, a storm brought gusts of up to 30 m sec^{-1} (recorded by a maximum gust recorder). It was not possible

(6) The levels used: 0.55, 1.2, 1.95, 2.8, 3.8, and 5.0 metres.

Plate 6

The wind profile mast with the Anemometers in place.

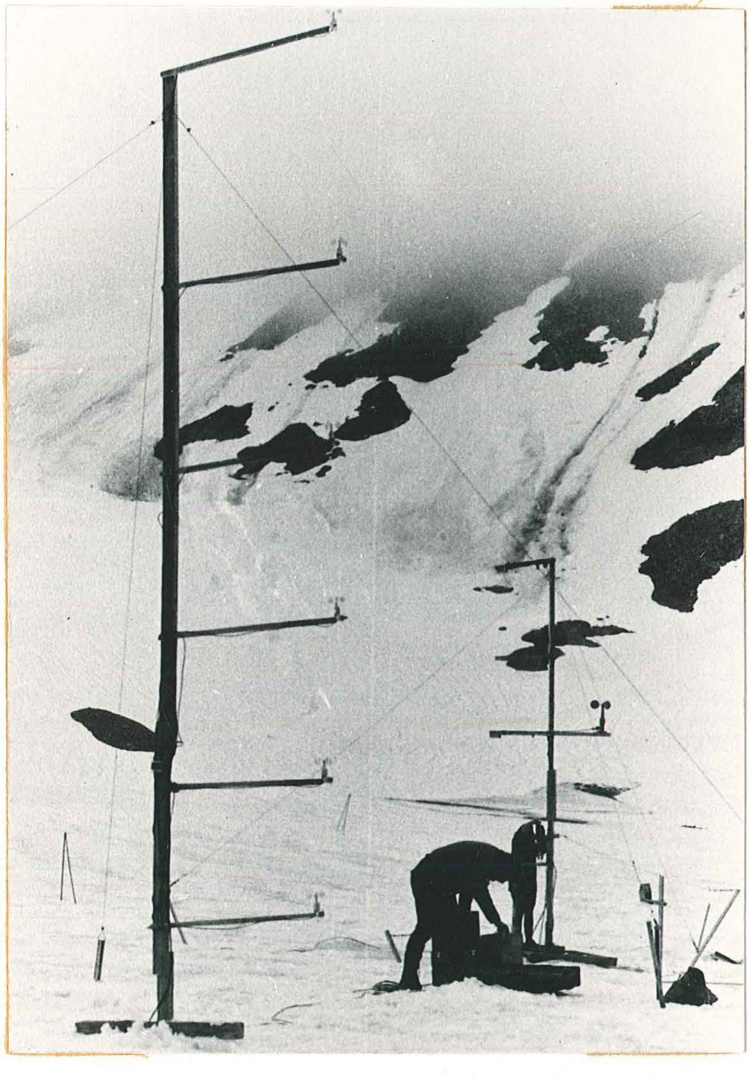
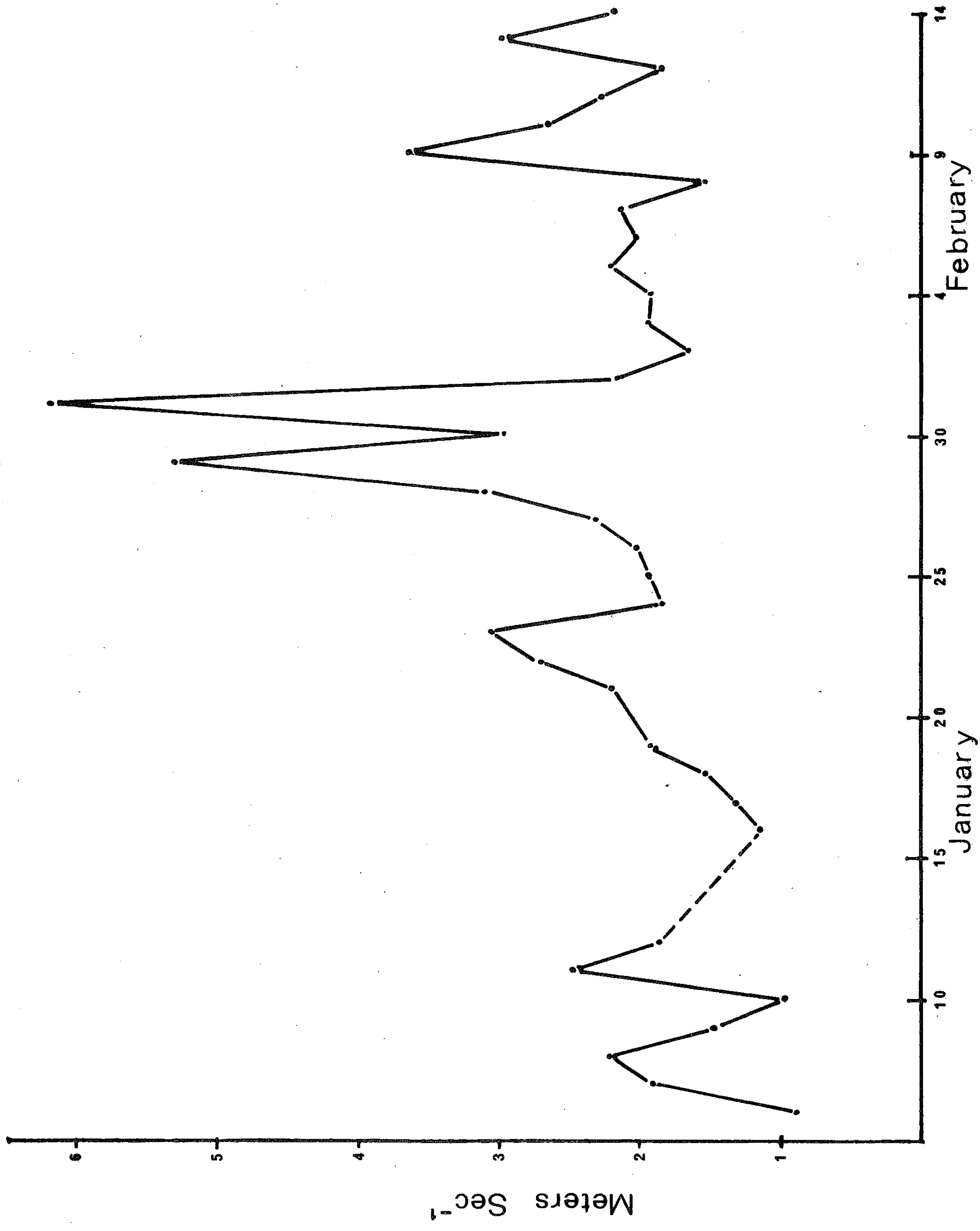


Figure 7: Mean Daily Wind Speed

Figure 7



to measure the winds associated with this at the instrument site because the mast proved to be unstable under these conditions and had to be lowered. A minimum wind speed of 0.17 m sec^{-1} was measured on January 6 from a 10 minute wind run at 1500 hours.

Although the mean wind speed for the study period was low, periods of complete calm were very sparse and when they did occur, they were usually of between 10 minutes and 3 hours duration. For example, of the 206 ten minute runs of wind between 0600 and 1800 hours, only 4 recorded a wind speed of less than 0.017 m sec^{-1} and only on two occasions were calm periods recorded at two consecutive 10 minute runs of wind (January 6 at 0600 and 0900 hours and January 8 at 0600 and 0900 hours). However, the possibility of longer duration periods of calm during the period from 1800 to 0600 hours when no 10 minute runs of wind were recorded must be borne in mind.

The predominate wind directions were from the northerly quarter (i.e. N.W TO N.E.). of the 172 observations of wind direction, 123 were from this quarter. The magnitude of the wind speeds show very little association with direction, however, from table 3:5 it is evident that there is a tendency for high wind speeds (above 5.00 m sec^{-1}) to be associated with winds from a southerly direction and very low wind speeds (below 1.00 m sec^{-1}) to be associated with winds from the north or north east with the intermediate velocities varying between both directions, although having a bias towards the north. However, observation of the direction from which the wind was originating at any one time, may be misleading, for direction was often

TABLE 3 : 5

A SAMPLE OF WIND SPEEDS[1] AND DIRECTIONS

	Speed ($m\ sec^{-1}$)	Direction
Below 1m sec^{-1}	0.17	N
	0.50	N.E.
	0.67	N
	0.83	N
1.1 - 4.9 m sec^{-1}	1.33	S.E.
	1.67	N
	1.50	N
	1.83	N
	2.00	N
	2.33	N
	2.50	S.E.
	2.67	N
	2.83	N
	3.00	S.E.
	3.03	N
	3.33	N
	4.00	S.E.
	4.33	N.E.
Above 5.0 m sec^{-1}	5.33	S.E.
	5.83	S.E.
	6.00	S.E.
	6.00	N
	6.17	S.E.
	6.33	S.E.
	7.17	S.E.
	9.17	N
	10.83	S.E.

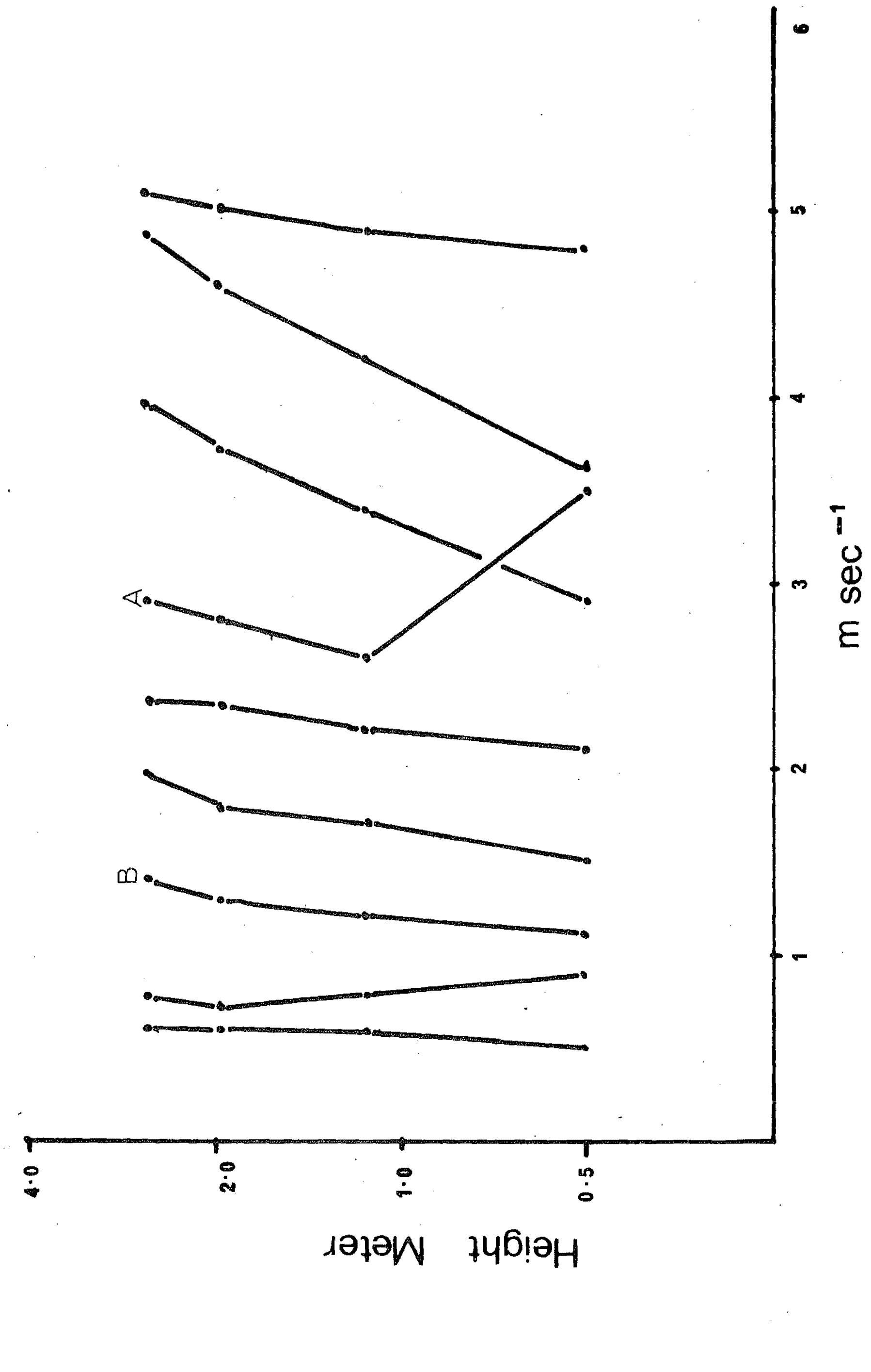
[1] These wind speeds were obtained from 10-minute runs of wind observed at either 0600, 0900, 1200, 1500 or 1800 hours.

difficult to ascertain because of rapid fluctuations in the wind direction probably caused by eddies induced by the enclosed nature of the valley itself. It was noted on many occasions that when moderate wind speeds (1.1 to 4.9 m sec^{-1}) were recorded, the wind on the glacier fluctuated between the Northwest and East while it was observed from cloud movement above the valley that the wind was mainly from the west or south. This would tend to suggest that the wind direction as recorded on the glacier was in fact influenced by the confined nature of the valley, the wind being channelled in the valley and contained there by the confining walls, a suggestion that is reinforced by a consideration of the orientation of the valley (north-south).

The wind profiles measured with the miniature anemometers, showed for the majority of profiles that the wind speed increased with the logarithm of the height in the first 1-2 metres (see profile B in fig. 8), however, during certain periods it was found that the profile changed to one similar to profile A in figure 8. A decrease in wind speed with height in the first few metres above the ground is not an unexpected occurrence over a glacier and it is probably associated with a drainage of cold air down the glacier, this being particularly prominent at night (Wallēn, 1948). As the wind direction during times when these inverse profiles were measured was always from the north (i.e. down glacier) it seems reasonable to suggest that these inverse profiles are the result of down glacier drainage of cold air. It was noted in the field that this drainage often occurred on a day when the

Figure 8: A sample of wind Profiles

Figure 8



temperature at the instrument site was between 5.0 and 7.0°C but a correlation between the direction and the air temperature gave no significant results.

Wind profiles under neutral conditions should show a curve of uniform slope when plotted against the logarithm of height. (Grainger and Lister, 1966). This being the case, the profiles obtained in the present study would tend to indicate that the conditions were near neutral or slightly stable, a fact which is given further emphasis when the Richardson numbers (7) (a measured stability) are calculated for certain periods during the study (Richardson number of 0 indicates neutral conditions, above zero stable conditions, and below zero unstable conditions). Richardson numbers for the present study, when they could be evaluated, ranged from 0.02 to 0.16 indicating near neutral to slightly stable conditions. However, as Richardson numbers could only be calculated for six observations, it must be pointed out that the assumption of neutral conditions has little evidence to confirm it, and so must be considered as an assumption only. Only six calculations were possible because of the difficulty of extracting temperature profile data from the only source available, the recordings at 3 heights mentioned earlier.

On the assumption of neutral stability condition values for the surface roughness length were calculated from equation 6 (z_1 and z_2 were 0.55 and 1.2 metres respectively).

---

(7) Sellers (1969, p. 153) gives the following description of the Richardson Number. 'The Richardson number represents the ratio of the rate at which mechanical energy for the turbulent motion is being dissipated (or produced) by the buoyancy forces (free or natural connection) to the rate at which mechanical energy is being produced by inertial forces (forced or mechanical connection).'

The values obtained are given in table 3:6.

As only 46 of the 149 wind profiles undertaken were considered to be acceptable (on the criterion of displaying a linear increase in wind speed with the logarithm of the height), it was found to be impossible to distinguish any variation through time in the z_o values obtained over either ice or snow. Thus it was necessary to calculate the z_o values for each surface type and mean these to get a value that was as representative as possible of the roughness conditions associated with each surface type. However, as shown in table 3:6, it was possible to distinguish between z_o values on the basis of the wind speed at 1.2 metres.

This was especially pronounced for the values obtained over the ice surface (mainly because more usable profiles were obtained over ice, a fact due not to some inherent quality of ice but rather due to instrumentation difficulties experienced in the first part of the study).

Similar values to those given in table 3:6 have been found in other studies (e.g. Grainger and Lister 1966 p.104 give values of z_o obtained from 7 separate studies that range from 1.1cm to 0.01cm). A mean z_o for a 10 day period of 0.41 cm was found by Lougeay (1969, p. 79) and Sagar (1966, p. 32) found a range of values over snow from .001 to 0.4 cm.

B. Air Temperature

The air temperature was measured by an Assman aspirated psychrometer at 1.2 m above the surface at a frequency of once every 3 hours between 0600 and 1800 hours. Maximum and minimum temperatures were read from thermometers placed in a Stevensons screen at the instrument site. The diurnal

TABLE 3 : 6

CALCULATED SURFACE ROUGHNESS VALUES (Zo) FOR CATEGORIES OF MEAN HORIZONTAL WIND SPEEDS (BETWEEN .55 AND 1.2m) AND SURFACE CONDITIONS

Wind Speed m sec^{-1}	No. of Values	Zo Ice	Ranges about	Wind Speed m sec^{-1}	No. of Values Used	Zo Snow (cm)	Ranges about Mean
Below 1.00	5	1.25	0.94 - 1.83	Below 2.00	4	0.55	0.15 - 1.21
1.01 - 1.50	9	1.02	0.43 - 2.15	2.00 +	6	0.46	0.04 - 0.71
1.51 - 3.00	14	0.43	0.01 - 0.64				
3.01 - 5.00	5	0.27	0.001 - 0.52				
5.01 +	3	0.14	0.06 - 0.21				

temperature range (i.e. maximum and minimum temperature), is shown together with the daily mean temperature in fig. 9 . The range of temperature during the study period was from -4.2°C (between 1800 hours on January 28 and 0600 hours on January 29) to 16°C (at 1200 hours on February 14) however this latter value is in doubt because a malfunction in the aspirating device of the Assman psychrometer meant that the instrument had to be adapted for use as a sling physchrometer during the last two days of the study period and this probably led to erroneous results. The maximum temperature recorded in the Stevenson screen was also found to be in error because of poor aspiration within the screen and these temperatures had to be corrected by comparing the temperature recorded at various times inside the screen with that recorded outside by the Assman psychrometer. The adjusted maximum for February 14 of 14°C supports the suggestion above that the 16°C reading recorded by the psychrometer at 1200 hours on that day was in fact, in error.

An attempt was also undertaken to measure the temperature profile at three levels (1.2, 2.8 and 5 metres) at a frequency of once every 8 minutes, however, this attempt was not successful for upon returning from the field it was discovered that the data contained on the charts obtained in the field was incomprehensible mainly because of difficulty in matching the temperature measured by the Assman psychrometer, at 1.2 metres every 3 hours, with a trace given on the chart for the temperature at the same time.

It was discovered that a measured temperature of 'A' might be recorded by successive traces showing a

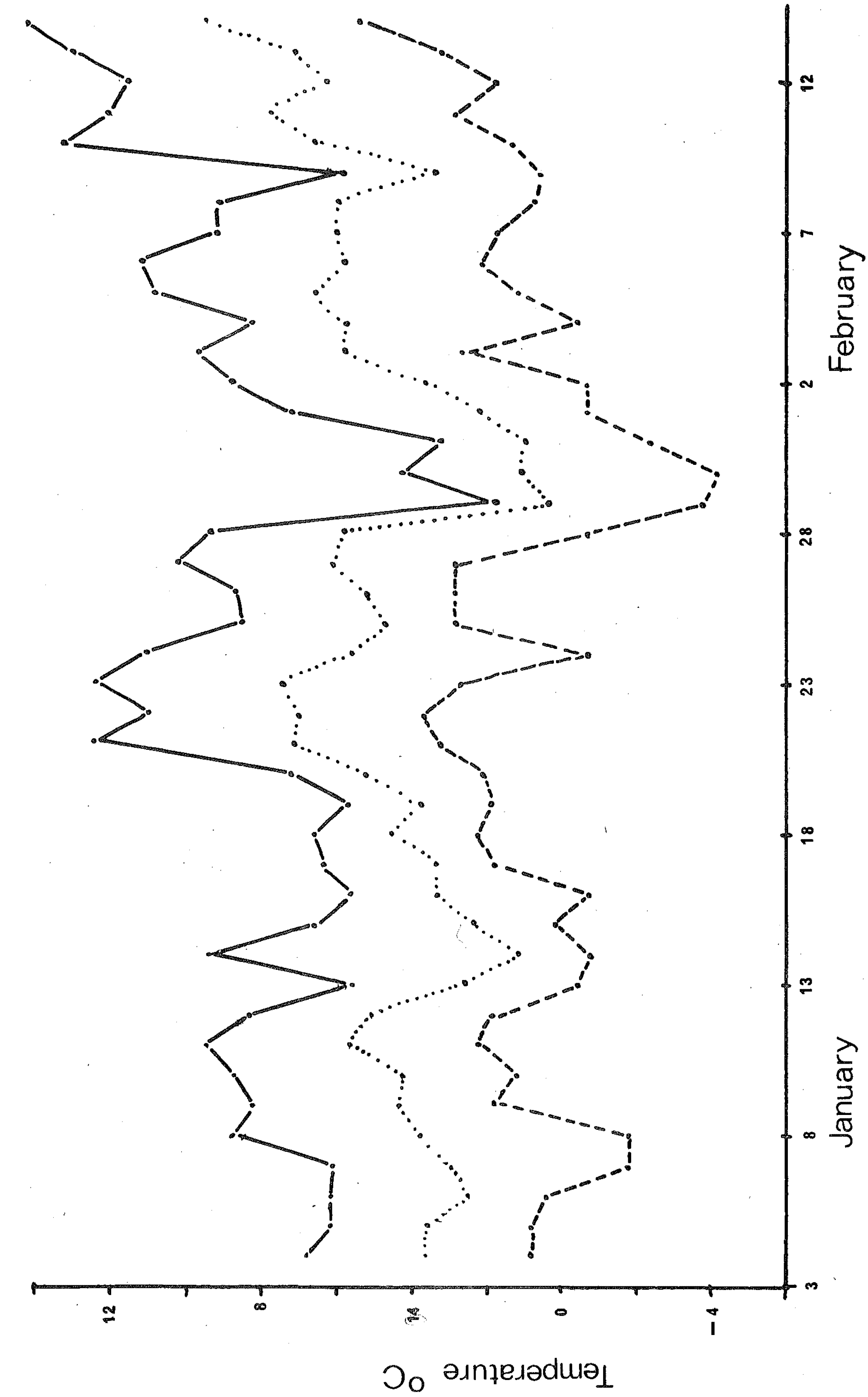
Figure 9: Mean daily temperature and the maximum and minimum temperatures.

——— Maximum

..... Mean daily temperature

----- Minimum

Figure 9



difference of anything up to 10 divisions (of the chart paper) in location. A possible explanation of this could be either a temperature response in the recorder itself or more likely, the result of radiant heating of the sensors on the mast, for although these were protected from radiant heating by metal shields, it is possible that because of poor aspiration they were still affected by this factor.

A comparison of cloud cover with temperature, showed that only on isolated occasions was there any significant correlation between these two variables. These occasions were mainly during storms originating from the S.E. and bringing rapid decreases in temperature which correlated with complete cloud cover (e.g. January 12 to 14 and January 28 to 31). This depressing of the temperature was also noted on other occasions (e.g. January 25) but the magnitude of the decrease in the temperature was much less than that which occurred during the storms. When the temperatures recorded were compared against the wind speed, a similar relationship (i.e. low temperatures with S.E. winds) was noted. Thus although a reduction in temperature occurred, the actual cause of this reduction is not definite but could be postulated that as winds striking the South Island of New Zealand from the S.E. are usually associated with a polar air mass (which one would expect to be at a relatively low temperature) the decrease in temperature recorded at the Ivory could be due to a colder mass of air passing over the area.

Winds from any other direction than the S.E. do not show this association with temperature.

C. Relative Humidity and Vapour Pressure

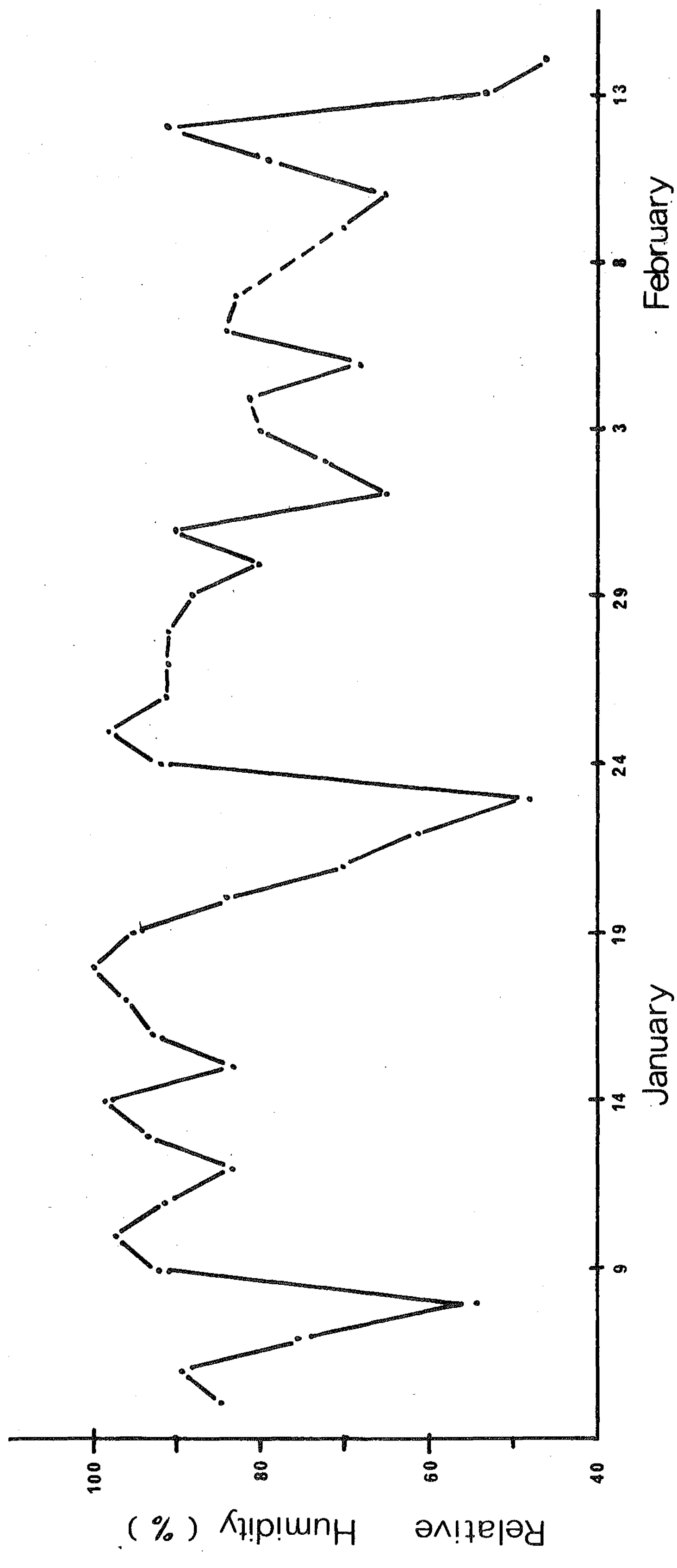
The relative humidity was measured once every three hours between 0600 and 1800 hours at 1.2 m with an Assman aspirated psychrometer. Daily mean values of the humidity were high (above 80%) for 29 of the 42 days on which it was sampled. On the remaining 13 days, the relative humidity ranged between 48% and 79% (see fig.10). The mean relative humidity for the total period was 81%. The minimum humidity recorded was 34% (February 14 at 1500 hrs) and the maximum 100%, however, within the range there were rapid fluctuations of the humidity (e.g. On February 1 the observed humidity at 3 hourly periods from 0600 hours were 70%, 63%, 58%, 45% and 69%).

An attempt was also made to record the humidity profile at the three levels mentioned in conjunction with the temperature profile, but as with the temperature profiles very little data could be extracted from the charts.

Vapour pressure values (in mm Hg) were obtained from the relative humidity and temperature data obtained at the 1.2 m level. The daily mean values for vapour pressure have been plotted in fig. 10. The vapour pressure at the surface was calculated from an assumed relative humidity of 100% and a temperature of 0°C. This assumption has been used by many investigators before (e.g. Lougeay, 1969) for it has been reasoned that with a melting surface (a situation that was evident for all but one day of the period under discussion) the humidity in the first few millimetres above the ice or snow will be at saturation point because of the amount of water available. It is evident from the

Figure 10: Mean Daily Relative Humidity

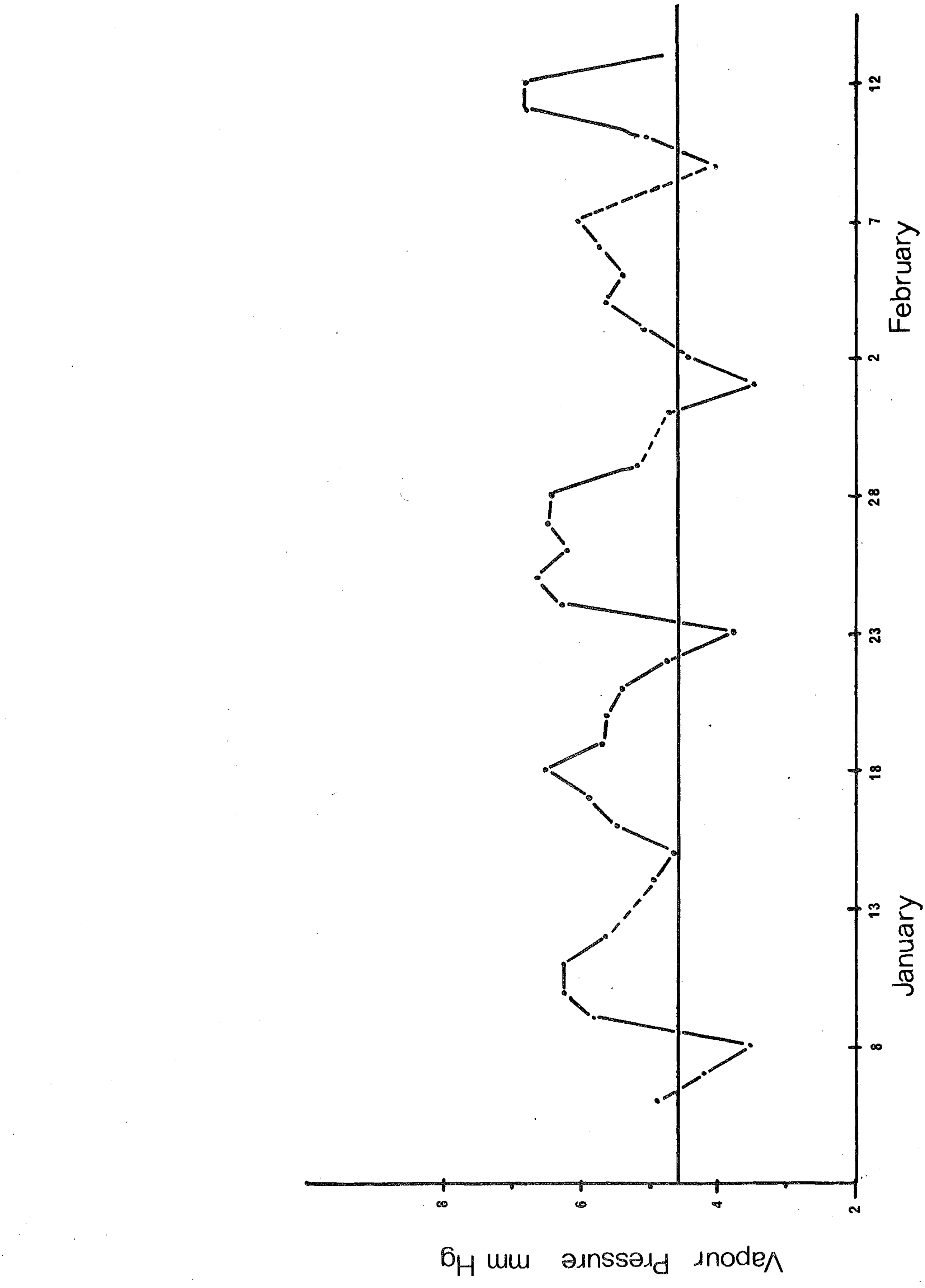
Figure 10



Relative Humidity (%)
100
80
60
40
9
14
19
24
29
3
8
13
January
February

Figure 11: The Mean daily values of Vapour Pressure measured at 1.2 m, and the assumed value at the surface.

Figure 11



Vapour Pressure mm Hg
2
4
6
8
8
13
18
23
28
2
7
12
January
February

positive vapour pressure gradient which would indicate that condensation of water vapour was likely to be occurring at the surface. Only on 6 occasions was the daily mean vapour pressure gradient negative (January 7, 8, 23, and February 1, 2, and 9). These daily mean values however gave a false indication of the situation for it was often found that for periods of between 1 to 3 hours the vapour pressure gradient was negative on days that registered a positive daily mean value, (e.g. on February 3, at 0600 and 1200 hours the vapour pressures at 1.2 metres were 3.91 and 4.32 mm Hg respectively, while the vapour pressure at the surface was assumed to be 4.57 giving a -ve gradient i.e. a decreasing vapour pressure with height).

D. <u>The Calculation of Sensible Heat Flux</u>

Equation (5) was used for the calculation of the daily values of this flux. However, with the use of this equation certain assumptions had to be made. As mentioned previously, neutral stability conditions are necessary for the application of the aerodynamic equations and as it was only partially proven that neutral stability conditions were encountered at the Ivory, neutrality must be assumed. With this assumption it is also necessary to assume that the temperature profile is logarithmic, that is, that the temperature decreases or increases linearly with the logarithm of height.

As temperatures at two levels were not available, it was necessary for the purpose of computation to assume that the surface was at $0^{o}C$. This assumption is not unreasonable as it has been found by many investigators (e.g. Wallen (1948) and Hubley (1957)), that ablation only begins to be registered once the snow pack or the glacier ice has reached 0°C (all incoming energy up to this point being used to increase the temperature of the ice or snow). This assumption was given some quantitative reasoning in the present study by the fact that little or no heat flow was observed through the snow pack, and profiles taken within the snow pack registered a temperature of 0°C throughout the snow depth. However, these profiles were only observed during times when the temperature was above 0°C (i.e. during the period from 0600 to 1800 hours), at other times it is probable that some heat flow through the snow pack was occurring but no quantitative assessment can be placed on this.

As the wind speeds recorded at the instrument site were those at the 2.8 m level, it was necessary to adjust the measured values to figures that represented the wind speed at 1.2 metres. This was achieved by the use of the equations below.

$$U_* = \frac{K \cdot U_z \cdot 0.4343}{\log \frac{z}{z_0}} \text{ cm sec}^{-1} \qquad (8)$$

(from Sagar 1966 p. 47)

where

U_* is the so-called friction velocity

K is Von Karman's constant (0.4)

U_z is the wind speed at height z (cm sec^{-1})

z_0 is the roughness length

then using the value of U_* in the equation,

$$U_z = \frac{U_*}{K} \ln \frac{z}{z_0} \text{ cm sec}^{-1} \qquad (9)$$

(from Sagar, 1966, p.47)

where

$\ln \frac{z}{z_0}$ is the natural logarithm of the ratio of the height to the roughness length.

Calculations of the sensible heat flux for periods of similar wind speed and temperature were undertaken and from these it was possible to calculate daily mean sensible heat flux values between the surface and 1.2 metres.

To categorise the wind speeds recorded (by the large Ota Keiki anemometer) at the 2.8 m level, with those recorded by the Rimco miniature anemometer at the same level during the wind profile measurements, it was necessary to compare the results obtained from the two during the same time periods. The regression analysis undertaken to achieve this comparison revealed that the values recorded by the Ota Keiki anemometer were within 0.2 m sec^{-1} of those from the miniature anemometer 99% of the time. Thus it was concluded that there was no need to adjust those measurements obtained from the Ota Keiki anemometer, for this error of $\pm$ 0.2 m sec^{-1} was with the range of error that was created by smoothing a number of the wind profiles. Thus with no corrections necessary to the values recorded by the Ota Keiki anemometer, it was then possible to apply equations 8 and 9 to obtain the wind speed values (for 10 min runs of wind) at 1.2 m so that these could be used with the respective z_0 values in equation (5). The values obtained for the sensible heat flux are given in fig. 12.

The flux of sensible heat towards the surface (which occurred on all days), was relatively high, compared with both the values for the net radiative flux, and values for the sensible heat flux obtained by other workers in this

Figure 12 - Sensible Heat Flux

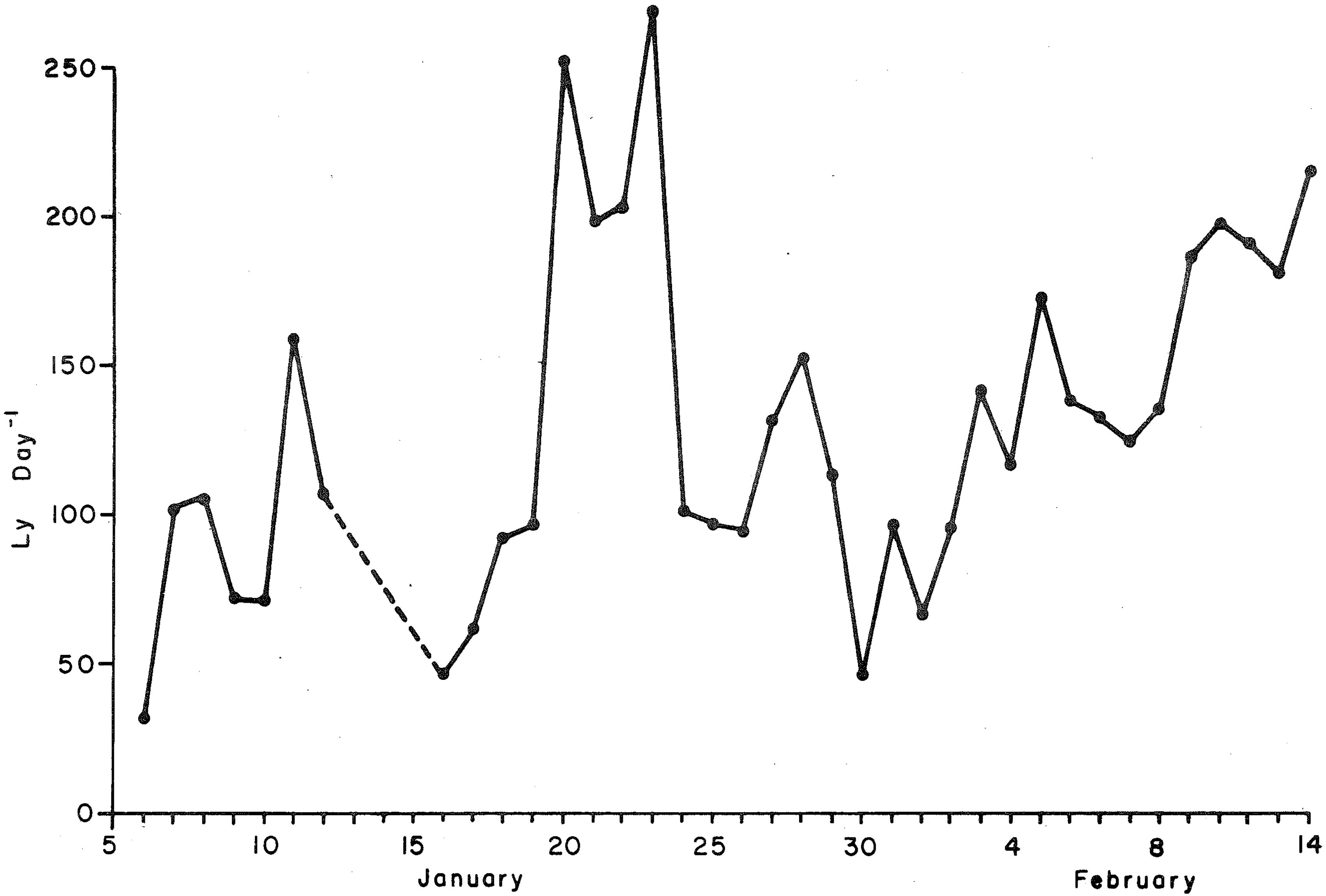

250
200
150
100
50
0
Ly Day-1
5
10
15
20
25
30
4
8
14
January
February

Figure 12

field (e.g. Sagar, 1966, Lougeay, 1969).

It must be noted, however, that because of differences in latitude, altitude and general weather conditions on which other studies have been undertaken, it is difficult to compare the values obtained in this study with those obtained in other studies, just as it is difficult to apply the values obtained at the Ivory to any other glacier, even within New Zealand.

E. Calculation of Latent Heat Flux

As 'a complex relationship exists between the moisture content and the flux of water vapour in the atmosphere near the ground' (Sagar 1966 p. 34), the aerodynamic equation for the latent heat flux was not used in the present study. Instead, the latent heat flux was calculated by use of the Bowen Ratio (Bowen 1926). This ratio gives a value for the relative contribution of both latent and sensible heat under given conditions of temperature and moisture. The equations used were as follows:

$$RB = 0.46 \frac{(T_z - T_s)}{(e_z - e_s)} \cdot \frac{P}{P_o} \qquad (10)$$

(From Sagar, 1966 p. 47)

where

R_B is the Bowen Ratio.

T_z is the temperature at height z (°C)

T_s is the temperature at the surface (°C)

e_z is the vapour pressure at height $_z$ (mm Hg)

e_o is the vapour pressure at the surface (mm Hg)

P is the station barometric pressure (mm Hg)

P_o is the sea level pressure (mm Hg)

The pressure P was measured with a

P_o was calculated by

$$\Delta \Phi_{s_1} = \Delta \Phi_{s_2} - \Phi_2 \frac{T_o}{T_v + T_{mv}} \quad (11)$$

(Smithsonian Meteorological Tables p. 204)

where

Φn is the geopotential (height) corresponding to a station pressure Pn

To is the temperature of the ice point (273.16°K)

Tmv is the mean adjusted virtual temperature

To obtain the latent heat flux from this ratio, the sensible heat flux must first be obtained. Once this is achieved, the ratio

$$RB = \frac{H}{LE} \quad (12)$$

may be arranged to obtain

$$LE = H. R_B \quad (13)$$

In the present study, only daily values of LE were calculated. This involved using the daily mean temperature, the daily mean vapour pressure, daily mean pressure and the daily mean pressure adjusted to sea level. These combined in the appropriate manner into equation B, gave values for R_B ranging from -17.7 to 10.96. However, the magnitudes of of these ratios was considered erroneous, probably due to the calculation of the P_o values, so a comparison was undertaken using the equation

$$\frac{H}{LE} \quad \frac{Cp \Delta \theta}{L \Delta q} \quad (14)$$

(Sellers 1965 p. 145)

where

Θ is the potential temperature (found from table 75, p. 308-313, Smithsonian Meteorological tables)

q is the specific humidity

L is the latent heat of vapourisation

Cp is the specified humidity of dry air

and $q = 622 \frac{e}{p}$ g kilo^{-1}

where

e is the vapour pressure

p is the pressure

(Haynes, 1947, p. 114)

The values obtained from equation 14 ranged from -0.6 to 1.6 and were used in place of the above values to obtain the ratio of the latent heat flux to the sensible heat flux.

The values for the latent heat flux from these calculations are given in fig. 13 and table 3:7. There was a wide range of values; from -39.3 ly day^{-1} (on January 7) to 275 ly day^{-1} (on January 20) giving a total value of 2642 ly for a 34 day period(8).

As negative values for the latent heat flux are few in the present study, it would appear that evaporation played only a minor role in the removal of mass from the glacier surface. However, as these values for the latent heat flux are only daily they tend to mask any evaporation that may bave occurred during any one day. For example, on February 3 at 0600 and 1200 hours the values recorded

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(8) Latent heat values were only obtainable for 34 days because of lack of data on the other days due to weather conditions and instrument malfunctions.

Figure 13: Daily Values for the LATENT HEAT FLUX.

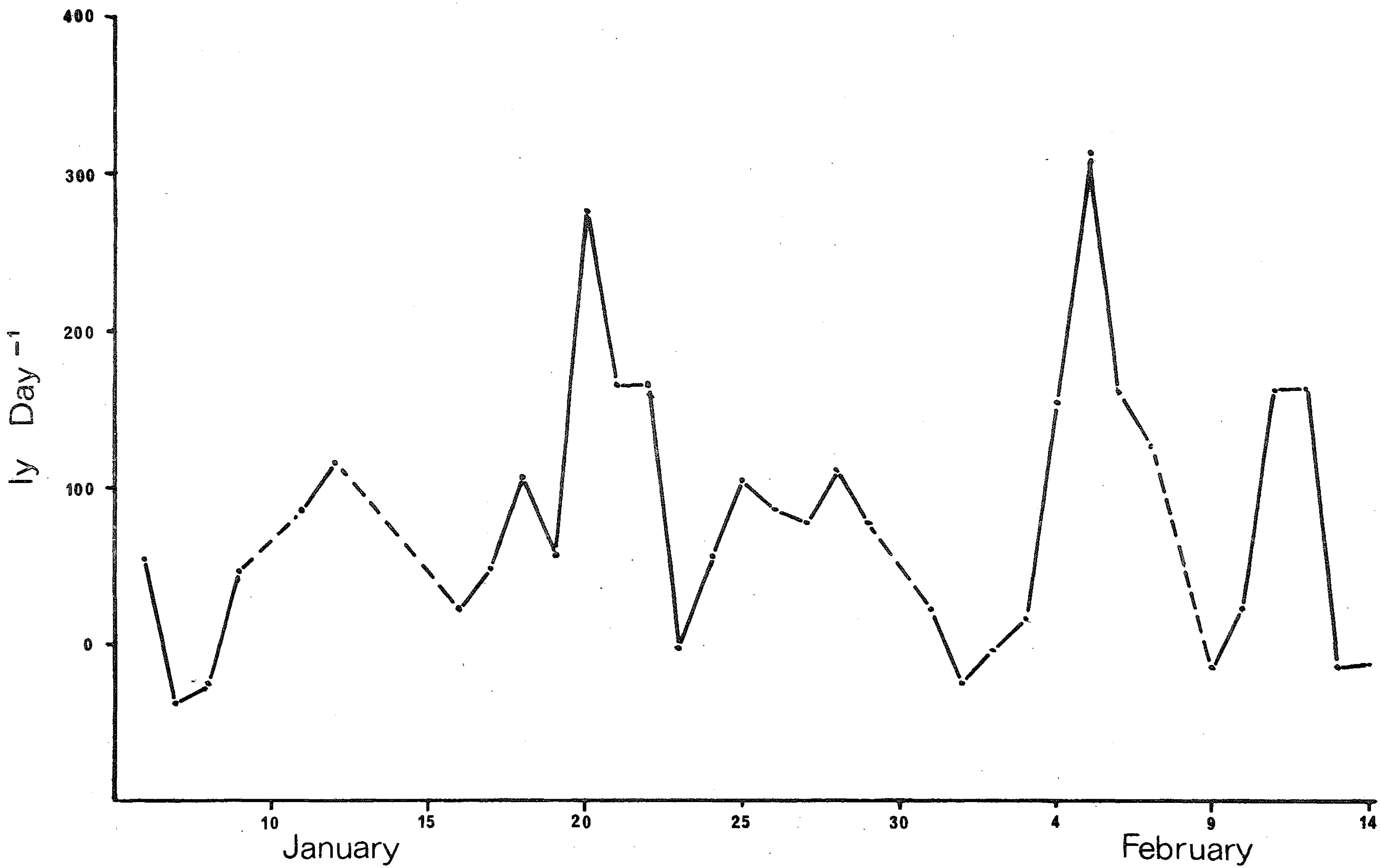


Figure 13

for the vapour pressure were negative suggesting that an upwards transfer of water vapour (i.e. evaporation) was occurring, however, in the evaluation of the latent heat fluxes, this evaporation is masked because the daily mean vapour pressure for that day was positive suggesting condensation at the surface (or a net transfer of latent heat towards the surface).

As no evaporation measurements were undertaken with the aid of lysimeters, it is difficult to put a definite value on evaporation at the Ivory. However, one would have expected evaporation to play a major role in removing the mass associated with surface changes as large as those observed at the Ivory glacier (see table 2:2) but as melting was observed to be very rapid, (although no figures can be obtained as yet for the run off from the glacier as this data is are in the custody of the Ministry of Works and has ve not yet been evaluated), and if the apparent volume of water that moved through the multitude of meltwater channels on the glacier is any indication, it is conceivable that the apparent lack of evaporation may in fact be a true indication of the situation.

F. Precipitation

Rainfall was measured in a small storage gauge of 254 mm capacity and by means of a Casella 'weekly' recording rain gauge. Snow fall was measured by reference to accumulation at the ablation stakes. This latter method is somewhat inadequate but was thought to be the best practicable means of measuring this parameter in view of the well-known difficulties of measuring snowfall amounts. The method was adequate for the purposes of this study for during the period over which the energy balance was evaluated, only 3 cms (at a maximum) of snow fell (on January 30).

The rainfall (see fig. 14) for the period under study was low compared to figures obtained for similar periods in the last two years (e.g. 1969 930mm, 1970 1020mm) only 563 mm of rainfall was recorded at the instrument site. It is evident that the majority of this rainfall occurred during two periods of intense rainfall between January 13 and 14, and during January 28 and 29 with falls of 164 mm and 294 mm respectively, being recorded.

It was postulated at the commencement of this study that rainfall might well be a major factor in the removal of snow and ice from the glacier surface. The consideration of rainfall as a heat input in the energy balance at a glaciers surface has frequently been neglected by workers in this field, or if considered, has always been found to be negligible.

The heat input of the rainfall was computed by:

$$P = C_w (T_p - T_s) P_r \qquad (15)$$

(Lougeay, 1969, p. 81)

where

P is the heat content of the precipitation

Cw is the specific heat of water

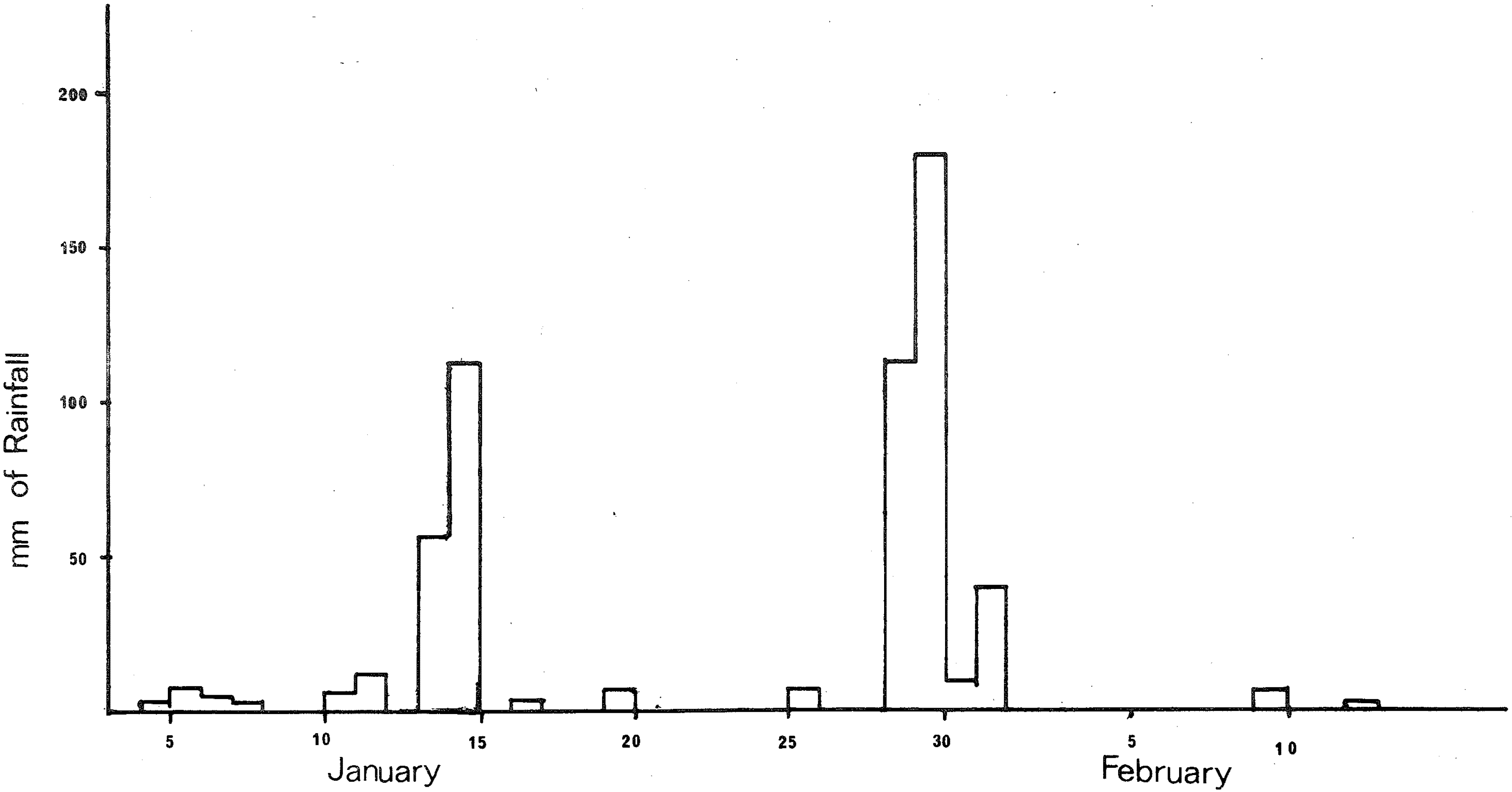
Tp is the temperature of the rainfall (°C)

Ts is the temperature of the surface (°C)

Pr is the amount of rainfall (grams)

The most difficult parameter to evaluate in this equation is the temperature of the rainfall as no satisfactory method has yet been devised to accomplish this task. In the present study, an attempt was made to determine this variable by using polystyrene containers with a

Figure 14: Daily Tables of Precipitation



mm of Rainfall
200
150
100
50
5
10
15
20
25
30
5
10
January
February

Figure 14

reservoir 152 cm^3 cut into the top. It was planned to collect the rainwater in these containers and measure its temperature, and the ambient air temperature at frequent intervals (15 minutes). This attempt was unsuccessful however, because the reservoir was too large with the result that by the time enough water had collected for its temperature to be gauged, the water temperature had reached equilibrium with the air temperature. The attempt was further complicated by Keas (large native parrots) which attacked the polystyrene ripping it to pieces. (see Plate 7). A further attempt was made using a vacuum flask but this was unsuccessful as it was found impossible to keep the flask upright because the Keas persisted in pulling it over until the glass within the flask shattered.

To obtain the temperature of the rainfall it was necessary to assume that this temperature was the same as the measured ambient air temperature, an assumption that has been used before (see Lougeay, 1969, p. 81). With the aid of this assumption the values for the heat content of the precipitation were calculated (see table 3:7). It was found from these computed values that only on January 28 and 29 were the heat inputs from the rainfall (80 lys and 37.5 lys respectively) of large enough magnitudes to be of significance in the daily energy balance.

IV. The Energy Balance and the Calculated Heat Sink from the Measured Surface Change

(A) Energy Balance

In table 3:7, are outlined the daily fluxes of the components of the energy balance as recorded at the Ivory glacier. The term (m) for the heat transfer of energy

Plate 7

The Rain Temperature Gauge after a Kea 'Investigation'

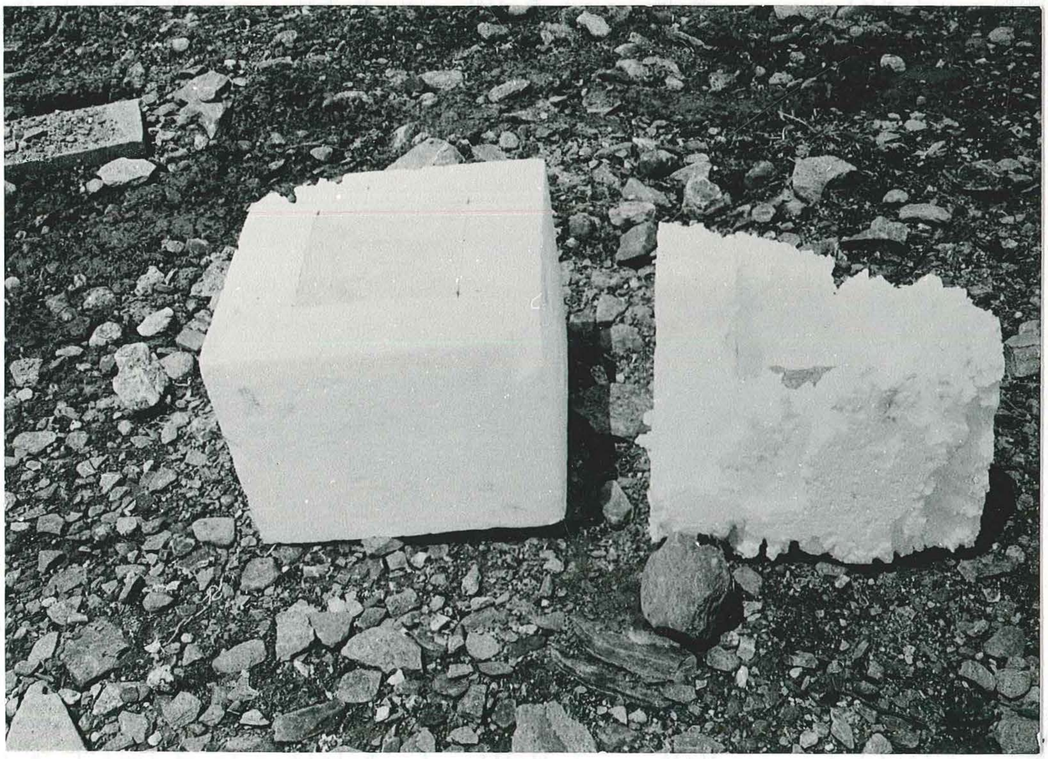


TABLE 3 : 7

THE DAILY VALUES FOR THE COMPONENTS OF THE ENERGY BALANCE AT THE SURFACE OF THE IVORY GLACIER AND THE POSSIBLE HEAT SINK ASSOCIATED WITH THE SURFACE CHANGE VALUES

All Units in Langley's Day^{-1}.

Date 1972	Net Radiative Flux (R)	Sensible Heat Flux (H)	Latent Heat Flux (LE)	Heat Content of Precipitation (P)	Total Heat Input	Heat Sink from Surface Change Values
Jan.						
6	132.0	32.8	54.7	1.2	220.7	128
7	125.2	101.0	-39.3	1.3	188.2	184
8	133.0	105.5	-27.7	0.0	210.8	200
9	85.3	73.4	40.8	0.4	199.9	104
11	164.0	151.2	87.1	4.5	406.8	344
12	98.2	107.1	117.8	0.0	323.1	288
16	66.1	47.5	22.6	0.8	137.0	120
17	97.3	62.2	49.5	0.3	209.3	208
18	100.5	90.3	108.2	0.1	299.1	296
19	64.0	97.6	56.4	2.1	220.1	192
20	128.0	250.6	275.0	0.0	653.0	296
21	137.7	199.7	164.1	0.0	501.4	424
22	182.2	203.0	165.2	0.0	551.0	474
23	123.9	269.7	-1.4	0.0	391.0	384
24	177.6	101.1	54.7	0.2	333.6	320
25	96.4	130.8	101.9	4.3	333.4	312
26	182.1	95.0	84.3	0.0	361.4	360
27	199.5	132.2	74.9	0.0	406.6	384
28	80.7	152.1	113.5	80.6	426.9	464
29	102.3	114.0	77.3	37.5	331.1	552
31	58.0	91.6	20.5	-0.2	169.9	168
Feb.						
1	114.6	66.5	-25.5	0.0	155.6	152
2	161.4	95.9	-2.7	0.0	254.6	192
3	199.4	140.2	16.0	0.0	355.6	344
4	145.4	117.5	151.6	0.0	414.5	200
5	191.0	173.7	312.7	0.0	677.4	432
6	239.0	138.2	160.3	0.0	537.4	384
7	191.1	133.9	127.5	0.0	452.5	176
9	195.3	130.5	-19.1	1.9	308.6	296
10	189.3	186.6	23.7	0.0	399.6	384
11	234.4	198.7	161.0	0.0	594.1	472
12	161.0	192.2	163.0	2.2	518.4	512
13	200.7	182.3	-15.1	0.0	367.9	176
14	236.6	215.4	-11.4	0.0	440.6	440
Total:[1]	5,129.	4,580.	2,642.	137.	12,351	10,771

[1] These totals only refer to the dates listed as a number of days have been excluded because of insufficient data.

from or to the underlying layers of the glacier has been neglected from this tabulation and earlier discussion as it was found to be negligible.

It is evident from table 3:7 that the relative importance of the energy balance components fluctuates. For example on January 10, the net radiative flux accounts for 48.0% of the total heat input, while the sensible and latent heat fluxes account for 26.5% and 24.8% respectively. By contrast on January 21 the relative contribution of the net radiative flux is only 37.4% whereas the sensible heat flux accounts for 48.8% of the total heat input. However, over the total period, (with the exclusion of those days for which insufficient data are available) the net radiative flux is the largest contributor to the energy balance (41.5%) followed by sensible heat (37.1%) and latent heat (21.4%). The values for the relative contribution of the fluxes are given in table 3:8 with some results from the other studies, the data for which was extracted from a table given by Paterson (1969, p. 58-61).

(B) Heat Sink Calculated from Surface Change Values

It is possible to calculate the heat sink associated with the surface change values by using the latent heats of melting (80 cal g^{-1}), evaporation (approx. 590 cal g^{-1}), and/or sublimation (approx. 680 cal g^{-1}), provided the contribution of each of these processes to the actual values of the surface change can be gauged.

In the present study, however, it was not possible to distinguish between the contribution of each of these processes but in order to have some reference against which the values for ablation obtained from the energy balance

TABLE 3 : 8

PERCENTAGE COMPARISONS OF THE ENERGY BALANCE COMPONENTS AT DIVERSE LOCATIONS

Location	Latitude (o - ′)	Surface	Elevation (m)	R.	H.	L.E.	Investigator
Ward Hunt Ice-Shelf, Ellesmere Island	83.12 N	Snow/Ice	15	100	-	-	Lister, 1962
White Glacier, Axel Heiberg Island	79.26 N	Ice	280	48	32	30	Andrews, 1964
Sveanor Snowfield, Spitsbergen	79.56 N	Snow	5	24	58	18	Sverdrup, 1935
Greenland Ice Cap	69.40 N	Ice	1000	86	14	-	Ambach, 1960
Penny Ice Cap, Baffin Is.	66.59 N	Snow	2050	61	30	9	Orvig, 1954
Barnes Ice Cap, Baffin Is.	70.14 N	Snow	1075	70	18	7	Sagar, 1966
Salmon Glacier, Canada	56.10 N	Snow	1700	75	15	10	Adkins, 1958

Continued -

TABLE 3 : 8

PERCENTAGE COMPARISONS OF THE ENERGY BALANCE COMPONENTS AT DIVERSE LOCATIONS

Location	Latitude (o - ′)	Surface	Elevation (m)	R.	H.	L.E.	P	Investigator
Blue Glacier Olympic Mts., U.S.A.	47.48 N	Snow	2040	60	37	3		La Chapelle, 1959
Hornkees, Austria	47.00 N	Ice	2260	53	35	12		Hoinkes, 1953
Central Fuyuksu Gl., Tien Shan, U.S.S.R.	43.00 N	Snow/Ice	3475	78	.... 22			Skeib, 1962
Ivory Glacier, Southern Alps, N.Z.	43.07 S	Snow/Ice	1500	41.5	37.1	21.4	0.1	Harding Present Study

(After Paterson 196 9/P58-61).

equation could be compared, values for the heat sink associated with the surface change have been calculated on the assumption that the heat available was used only for melting (i.e. for every 1g of negative surface change, 80 cal of heat were used). The results from this calculation are given in table 3:7. The values for these latter calculations show some large discrepancies when compared with the total heat input (ablation) values. For example, on January 20, the total calculated heat input was 653 ly whereas the calculated heat sink was only 296 ly.

On all but two days (January 28 and 29), the calculated heat input is greater than the calculated heat sink (using the assumption of melting only). This would suggest that surface change was brought about by melting plus some other factor, this factor being evaporation or sublimation. Thus the assumption of melting only is not confirmed by the results. If for the moment the values for the calculated heat input are considered to be correct, it is then possible, by subtracting the heat sink from the heat input and dividing this figure by 590, the latent heat of evaporation, (thus assuming no sublimation) to obtain values for the amount of ice or snow lost to evaporation. By means of this calculation it was found that the maximum value for this loss was only 0.15 cm water (on January 20). From this it can be concluded that evaporation is small to negligible in terms of the amount of material removed by this process over the Ivory. If sublimation also takes place, this loss could be even smaller

The two days (January 28 and 29) when the calculated heat sink is greater than the heat input are of interest.

It was postulated in Chapter 2, section 3c that the high rate of surface change that occur on January 28 and 29 might be caused by the influence of the intense rainfall measured on those two days. It was also postulated that a part of this surface change might be attributable to the removal of the granular crust of ice on the glacier's surface by the impact of raindrops (i.e. erosion). If this erosion was taking place, one would expect that the heat sink calculated from the surface change values would be of a greater magnitude than the heat input calculated from the energy balance, (i.e. erosion is not considered in the latter but will be registered as a heat sink in the former unless its occurrance is forseen and the values corrected accordingly).

As the values given in table 3:7 for the heat sink were not corrected for the possible occurrence of erosion, it is conceivable that the difference between the heat input and the heat sink for January 28 and 29 is an indication that erosion took place on those two days. To obtain the magnitude of this erosion, it is only necessary to subtract the heat input from the heat sink and divide the resulting value by 80 cal g^{-1}. The result of this in the two cases cited is an erosion of 0.46 cm water equivalent on January 28 and 2.79 cm water equivalent on January 29.

The above discussion is based on the assumption that the computed energy source values are correct. This must be qualified for the number of assumptions necessary to evaluate the components of the energy balance equation (e.g. a surface temperature of $0^{o}C$ and a surface vapour pressure of 4.57 mm Hg[9], plus the assumptions of logarithmic wind and temperature profiles) means that there is a distinct possibility of error arising in the calculation of these components and this must be borne in mind.

VI. Summary.

The daily flux of energy towards or away from the surface is dependent on the magnitude of the variables comprising the components of the energy balance. These variables have been discussed in the present chapter along with the resultant energy balance fluxes. It is evident that magnitudes of these fluxes were large, as were the daily values of the loss in mass from the surface.

A comparison between the heat available (computed from the energy balance) and the heat used (computed from the surface change values) showed that at times, large differences were evident between the values for these two factors. However in view of the assumptions that were necessary in order to ascertain the magnitude of these factors, it is not surprising that these differences exist, nor must it be concluded that only the assumptions could lead to error for instrument malfunctioning and the fact that no instrument is 100% accurate could also bring about error in the calculated energy fluxes. The heat sink values calculated from the surface change values could also be in error due to the assumption of melting being the only process by which mass was lost from the surface and through observational error in obtaining the surface change values. The magnitude of the individual values for the

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(9) This value for the vapour pressure was obtained by assuming saturation at the surface. Thus 4.57 mm Hg is the saturated vapour pressure over ice at 0°C. No adjustment in pressure being necessary (Smithsonian Meteorological Tables, 1966 p. 347)

components of the energy balance equation may be in doubt (because of the assumptions used) but it is difficult to put a quantitative judgement on either these values themselves or their percentage contribution. The proportinate contribution of the fluxes given by other workers in this field indicates that the results of separate studies undertaken at a variety of places and times can only be compared with difficulty.

CHAPTER
4

STATISTICAL ANALYSIS AND THE IMPLICATIONS ARISING FROM THIS

I. Introduction

In order to ascertain if any correspondence exists between the meteorological elements measured, and the energy fluxes calculated during this study, the measured surface change, a series of regressions were run on a 360-44 I.B.M. computer with the surface change values as the dependent variable.

These comparisons were undertaken using a polynomial regression programme. To facilitate ease of comparison, this programme was used as a simple linear regression programme by only calculating the first degree polynomial. A stepwise multiple regression was also undertaken in an attempt to discover whether there was a close enough relationship between a small number of easily measured variables (e.g. humidity, temperature and rainfall) and the measured surface change values to enable the latter to be assessed without the need to calculate the energy balance. The results obtained from both these undertakings are presented in the present chapter, along with the implications of these results.

II. The Polynomial Regression Analysis

The results of these regressions are shown in table 4.1

For the purpose of this analysis, daily mean and/or total values for a number of independent variables and all the components of the energy balance equation were

TABLE 4 : 1

RESULTS OF POLYNOMIAL REGRESSION OF ABLATION AGAINST VARIOUS PARAMETERS

Variables Compared	Regression Equation at 1 degree freedom	Standard Error of Estimate	Coefficient of Correlation	% Explained Variation
Ablation - Incoming Short-Wave Radiation (Si)	y=4.06+0.0003x	2.46	0.02	0.034
Ablation - Net Radiation (N)	y=1.88+0.015x	1.61	0.47	22.200
Ablation - Latent Heat Flux (LE)	y=2.40+0.013x	1.43	0.44	18.300
Ablation - Sensible Heat Flux (H)	y=1.60+0.018x	1.32	0.58	34.110
Ablation - Temperature (T)	y=1.94+0.36x	1.36	0.45	20.310
Ablation - Cloud Cover (C)	y=3.95+0.009x	2.47	0.01	0.006
Ablation - Wind Speed (U)	y=8.09+0.88x	1.50	0.23	5.150
Ablation - Atmospheric Pressure (Pa)	y=4.32+0.084x	1.70	0.28	6.728
Ablation - Precipation (Pr)	y=2.13+0.090x	1.30	0.33	19.460
Ablation - Humidity (Hp)	y=1.89+0.11x	2.21	0.27	7.290
Ablation - Vapour Pressure (He)	y=1.63+0.14x	2.43	0.23	5.290

correlated with the measured surface change values for each day or number of days on which the latter were obtained. The daily values refer to the 24 hour period between 1500 hours and 1500 hours. It was necessary to use this period to facilitate comparisons between the meteorological variables and the surface change, for the surface change was measured only once a day at 1500 hours.

(A) <u>The Heat Balance Components</u>

The highest correlation obtained with the aid of the first degree polynomial regression was that between the total daily sensible heat flux and the measured surface change. A moderate positive correlation was obtained with a multiple correlation coefficient of 0.58 and a percent explained variation by the fitted regression line of 34.1. By applying an 'F' test for significance it was found that this correlation was significant at the 0.01 level, a statistical significance that in the light of the figures given in table 3 ; 7 could be considered to be relevant to the real world.

Although there is a significant positive correlation between the two variables, the surface change values are not particularly sensitive to the latent heat flux, an occurrence that is reasonable when it is realised that theoretically the sensible heat flux is only one component in the energy balance equation.

There was a wide scatter around the regression line associated with the correlation of net radiation and the surface change signifying that the surface change is, also, not very sensitive to this variable. Although a positive correlation was evident between these two factors it was a weak one (correlation coefficient 0.472) there being only 22.2% of the variation between the two variables explained by the regression line.

The daily surface change values showed even less sensitivity to the daily latent heat flux giving a correlation coefficient of 0.444 and a percentage explained variation by the fitted regression line of 19.7. The daily precipitation values gave an even smaller multiple correlation coefficient (0.326) and both these latter two coefficients were not statistically significant at either the 0.05 or 0.01 levels.

From the above brief outline of the results of the polynomial regressions it is obvious that the individual components of the energy balance do not produce high correlations with the measured surface change.

When the daily totals of energy input calculated from the energy balance equation are regressed against the daily totals of the heat sink, a multiple correlation coefficient of 0.815 is obtained, this indicating that the result of the energy balance equation (i.e. the heat input) is a much more reliable indication of the heat sink than are its individual components.

However, the correlation is by no means perfect, suggesting that error is present in either the component parts of the energy balance or the method for the calculation of the heat sink from the measured surface change, both of which are probable.

(B) The Measured Meteorological Variables

The multiple correlation coefficients obtained from a number of regression analyses comparing the daily surface change values with such variables as daily mean cloud cover, daily mean temperature, daily mean relative humidity, daily mean wind speed, the daily mean pressure and daily total short-wave radiation income, were low. The highest correlation was that obtained for the temperature and surface change regression (0.451) and although this correlation was statistically significand at the 0.01 level, the correlation coefficient itself would suggest that there is only a weak relationship between the two variables.

The correlation coefficients obtained from the regression analysis of the daily mean relative humidity (0.267), the daily mean wind speed (0.227), the daily mean cloud cover (0.008), and the daily total short-wave radiation income (0.018) were not statistically significant at any level tested (i.e. 0.5 or 0.01). However, these low correlation coefficients do not necessarily mean that there is no relationship between the surface change and the variables measured, but it does mean that there is no linear relationship between these parameters using the units and time periods applied in this study. It may be that if a different 24 hour period had been chosen, high correlations may have been discovered, or yet again if the surface change had been sampled more frequently, it may have been possible to use mean figures for shorter time periods, which may have produced higher correlations.

III. Multiple Regression Analysis

The variables that were considered in this multiple regression analysis were:-

(a) The dependent variable

- the measured daily surface change.

(b) The independent variables -

(i) The daily income of short-wave radiation.
(ii) The daily mean relative humidity at 1.2 metres.
(iii) The daily mean temperature at 1.2 metres.
(iv) The daily mean vapour pressure at 1.2 metres.
(v) The daily mean pressure.
(vi) The daily total of precipitation.
(vii) The daily mean wind speed at 1.2 metres.
(viii) The daily mean cloud cover.

These eight independent variables were selected in a number of combinations in an attempt to find that combination which gave the highest correlation with the measured surface change.

(A) Results

The programme used, orders the independent variables as to their position within the regression equation, and gives the multiple correlation coefficient and 'F' value for each step.

1. The First Selection

The first variable entered into the regression was rainfall (see table 4 : 2A). This gave a multiple correlation coefficient of 0.326 which was not significant by the 'F' test at either the 0.5 or 0.01 levels. The multiple correlation coefficient (adjusted for the degrees of freedom), increased to 0.440 with the introduction of the total incoming short-wave radiation into the regression equation, and by the 'F' test this was found to be

TABLE 4 : 2A

THE ORDER OF SELECTION AND THE CORRELATION COEFFICIENTS OBTAINED IN THE FIRST SELECTION OF THE MULTIPLE CORRELATION PROGRAMME

Variables Entered[1]	Correlation Coefficient	Level at which Significant
A+Pr	0. 326	Not significant
A+Pr+Si	0. 440	0. 5
A+Pr+Si+Pa	0. 453	0. 5
A+Pr+Si+Pa+T	0. 616	0. 01
A+Pr+Si+Pa+T+C	0. 642	0. 01
A+Pr+Si+Pa+T+C+U	0. 692	0. 001
A+Pr+Si+Pa+T+C+U+Hp	0. 681	0. 001

1 The symbols used represent:

A - Ablation - daily mean.
Pr - Precipitation - daily total.
Pa - Atmospheric pressure - daily mean.
T - Temperature - daily mean.
U - Wind Speed - daily mean.
C - Cloud Cover - daily mean.
R - Net Radiation - daily total.
Si - Short-Wave Radiation Income - daily total.
Hp - Relative humidity - daily mean.

These apply to Tables 4 : 2A, 4 : 2B and 4 : 2C.

significant at the 0.5 level. With the introduction of the daily pressure values the adjusted multiple correlation coefficient increasing once more to 0.453, which was only significant at the 0.5 level.

The fourth step in the regression introduced the daily mean temperature, and this increased the adjusted multiple correlation coefficient to 0.616, the correlation becoming significant at the 0.01 level. A further increase in this coefficient to 0.642 was achieved by the introduction of the daily mean cloud cover, and yet a further increase to 0.692 by the introduction of the daily mean wind speed. Both these last two coefficients were significant at the 0.01 level, and in the latter case at the 0.001 level. However, the introduction of the last variable humidity (measured in %) reduced the coefficient to 0.681.

A further selection using the same variables as those just described, with the exception that vapour pressure values were used in the place of the relative humidity values, gave the same results as the first selection up to and including the introduction of the wind speed values. However, with the introduction of the vapour pressure values, the multiple correlation coefficient decreased to 0.679, a slightly smaller value than that obtained by the introduction of the relative humidity values.

2. <u>The Second Selection</u>

In this selection (see table 4 : 2B) the net radiation values were used in the place of the incoming

TABLE 4 : 2B

THE ORDER OF SELECTION AND THE CORRELATION COEFFICIENTS
SELECTION 2.

Variables Entered	Correlation Coefficient	Level at which Significant
A+Pr	0. 326	No significance
A+Pr+Pa	0. 415	0. 5
A+Pr+Pa+T	0. 630	0. 001
A+Pr+Pa+T+U	0. 648	0. 001
A+Pr+Pa+T+U+C	0. 678	0. 001
A+Pr+Pa+T+U+C+Hp	0. 681	0. 001
A+Pr+Pa+T+U+C+Hp+R	0. 671	0. 01

short-wave radiation values, all other variables remaining as they were in the first selection. Rainfall was again the first variable selected by the programme and gave the same multiple correlation coefficient as in the first selection. Pressure was selected next, giving a multiple correlation coefficient of 0.415, which was significant at the 0.5 level. The introduction of the temperature values in the third step increased the correlation coefficient to 0.630. The next three variables to enter the regression (wind speed, cloud cover, and relative humidity) increased the multiple correlation coefficient by only 0.033 (to 0.681) and the last variable to enter the regression, net radiation, reduced the coefficient to 0.671.

3. The Third Selection

In this regression the variables used were atmospheric pressure, temperature, wind speed, cloud cover, relative humidity and incoming short-wave radiation, all entering the regression in the order given (see table 4:2C). The adjusted multiple correlation coefficient for this regression attained a value of 0.518 (significant at 0.01) by the second step with the introduction of the temperature values. With the introduction of the wind speed values in the third step, this coefficient was increased to 0.619, which was significant at the 0.001 level. The addition of cloud cover and relative humidity increases the adjusted multiple correlation coefficient still further, to 0.674, while retaining significance at the 0.001 level. It is not until the last step with the introduction of the incoming short-wave radiation values, that the level of significance decreased to 0.01, and the adjusted multiple correlation

TABLE 4 : 2C

THE ORDER OF SELECTION AND THE CORRELATION COEFFICIENTS

SELECTION 3.

Variables Entered	Correlation Coefficient	Level at which Significant
A+Pa	0. 278	Not significant
A+Pa+T	0.518	0. 01
A+Pa+T+U	0. 619	0. 001
A+Pa+T+U+C	0. 669	0. 001
A+Pa+T+U+C+Hp	0. 674	0. 001
A+Pa+T+U+C+Hp+Si	0. 665	0. 001

coefficient reduced to 0.665.

4. The Fourth Selection

There was only one other selection which gave multiple correlation coefficients that were significant at the 0.01 or 0.001 levels. This was the combination of relative humidity, temperature and wind speed. These gave an adjusted multiple correlation coefficient of 0.543 which was significant at the 0.01 level.

IV. Implications.

The results presented in this chapter indicate that there is no apparent combination of variables that will give a high correlation with the daily measured surface change. The highest correlation that was achieved (0.692 in the first selection), although statistically significant, is not high enough to enable a relatively accurate estimate of the surface change to be gauged by just obtaining values for the more easily measured meteorological variables.

The results obtained, however, do suggest that there are some variables to which the surface change is more sensitive. For example, the introduction of the temperature values appears to increase the multiple correlation coefficient considerably (e.g. in the first selection, this coefficient is increased by 0.163; in selection two it is increased by 0.215, and in selection three it is increased by 0.240 - all these increases resulting from the introduction of the temperature values).

As well as suggesting that some variables are more significant in terms of the measured surface change values than others, the results also suggest that moderate correlations are possible with a number of combinations of various variables. In the first selection, a correlation coefficient of 0.692 was obtained from the combination of six of the seven variables considered. By removing just one of these variables (incoming short-wave radiation) a correlation of 0.681 was obtained in selection two, and by yet another deletion (precipitation), a correlation coefficient of 0.674 was obtained. This suggests that the inter-relationship between the meteorological variables as measured is complex, with the relative importance of each in relation to the rest being variable.

The data for these regressions were used in the units in which they were measured, with the exception of the relative humidity which in one selection was computed in units of vapour pressure. The results presented in the last paragraph of sub-section II A (i) of this chapter pertaining to the difference in the correlation coefficient obtained by using relative humidity and then vapour pressure would tend to suggest that if these meteorological variables used in this regression analysis were in different units to those actually used, the correlations may have been considerably changed for it is evident from this sub-section that a change in the units used to express water vapour content of the atmosphere brought about a difference (although light in the particular case under discussion) in the degree to which the measured variables correlated to the measured surface change. Tuede et al (1970) undertook a regression programme in an attempt to correlate certain meteorological variables with the discharge of water from a number of glaciers. From the analysis that was undertaken, it became evident that '.... the products of temperature and precipitation, or temperature and wind speed, were the most important to describe the water discharge. As the third term the air temperature appeared in all regression equations'. (Tuede et al 1971 p.106). It was also found in this study that the incoming radiation showed very little correlation with the discharge (a situation evident in the present study). This study obtained multiple correlation coefficients for the above combinations as high as 0.90; however to achieve this it was necessary to weight the variables.

If the assumption is made that the stream discharge from a glacier can be equated with the measured surface change values, from the previous discussion in this section it might be concluded that had the values used in the present study been weighted, much higher correlations may have resulted, for there is the suggestion in the correlations obtained that temperature plus rainfall, pressure, and wind speed, when correlated against the surface change give proportionally higher correlation coefficients than those obtained by any other combination of variables. (For example, temperature when combined with rainfall and pressure gives a correlation coefficient of 0.630 which, after the introduction of three more variables, only increases to 0.681.)

Tuede et al (1970) also used slightly different units to those used in the present study (e.g. the wind speed variable was expressed in daily run of wind by Tuede whereas in the present study, mean daily wind speed totals were used) reinforcing the suggestion made earlier that had the variables compared in the present study been expressed in other units, the correlations may have been different. However, it is not possible to say in what direction this change, if any occurred, in the correlation coefficients could take place.

V. Summary

The surface change values do not appear to be particularly sensitive to any one variable or any one combination of variables. Only when a comparison is made between the daily heat input and the daily heat sink, does there appear to be a significant correlation. However, as no correlations were undertaken with the variables weighted in any way, it cannot be concluded that the surface change for any one period can or cannot be evaluated by just measuring a number of the more easily measured meteorological variables. The analysis undertaken suggests that relationships exist between the variables compared, but a more sophisticated technique than that used would be needed to unravel the complex interdependence of the meteorological variables to enable the surface change to be calculated without becoming involved with the intricacies of the energy balance approach.

CHAPTER

5

CONCLUSION

Previous studies of the energy balance at the surface of a glacier have shown that the relative importance and magnitude of the various sources of energy can and do vary considerably over both time and space. It has become evident from previous work that a complex relationship exists between the climatic parameters, and this relationship affects the magnitude and direction of the relevant heat fluxes at the glacier's surface.

This present study has endeavoured to evaluate the flux of energy to and from the surface of one small New Zealand glacier in an attempt to gain a greater understanding of the conditions conducive to the removal of mass from that glacier's surface. It must be emphasised that the results obtained are only applicable to that portion of the Ivory Glacier studied and only for the time period of the study itself. This does not mean however that this study was purely an academic exercise in the application of theory to reality, for from this study has been gained a measure of the contribution to, and the effect of, the various climatic elements as they relate to the existence of the Ivory Glacier.

The relative contributions of the energy balance components to the total energy input at the surface of the Ivory as given in Chapter Three, indicate that over the period between January 5 and February 14 the major source of energy was radiation, with sensible heat was next in importance and the latent heat the least important (discounting the heat input from precipitation which over the total period was negligible). However when daily totals were considered, it was discovered that the relative contribution of the energy balance components varied considerably and radiation in this case was not always the major energy source.

The change in the relative contribution of these components was not due solely to a change in the magnitude of just one, but rather to a change in all three, and on isolated occasions during storms to four (with the inclusion of the heat input from rainfall). This would suggest that a relationship exists between the general weather parameters and the energy flux, a relationship that is evident, at least theoretically, when the equations used to calculate the energy balance components are considered.

The accuracy of the energy balance calculations can only be gauged from actual measurement of the mass loss from the surface of a glacier. Chapter Two involves a description of the methods used and the results obtained from such an undertaking within the present study and although the qualitative analysis undertaken revealed little to indicate the reasons for the large spatial and temporal differences in the surface change values obtained, it did never the less produce suggestions such as the possible importance of storms (i.e. rainfall) in accounting for the high rates of surface change measured on some days. Of more importance however was the comparison between the heat sink (calculated from these surface change values) and the heat input, for from this comparison it was discovered that overall there was a greater heat input than loss. This suggested that either, the values for the respective fluxes were in error or that evaporation was taking place which was not being accounted for in the calculations of the heat sink. The assumptions used to calculate the heat sink would suggest that the latter case may be the more correct, especially as the loss of mass associated with the discrepancies in the two totals (if assumed to be unaccounted for by evaporative loss) would only account, at the most, for 0.2 cm water equivalent.

The possibility or error in the calculation of the energy balance terms cannot be discounted, for a number of basic assumptions were made which could affect the results of the calculations, especially if the actual meteorological conditions over the glacier differed from the assumed conditions, and it is highly likely that this occurred.

The attempt to find significant, meaningful correlations between any one or combination of the standard meteorological parameters and the measured surface change was unsuccessful. However there were suggestions in the results obtained that by 'manipulation' of the units in which the parameters were expressed and/or by weighting the parameters, more significant relationships may have been discovered. By considering the apparent complexity of the inter-relationship between the meterological parameters that is suggested by both the qualitative and quantitative analyses undertaken in this study, this lack of correlation is not surprising - this lack of correlation however has a positive side as well as a negative side for its very occurrence could well be perceived as the justification for the adoption of the energy balance approach.

FURTHER RESEARCH

The one study undertaken on the Ivory Glacier should only be the beginning of a continuing study of the energy balance over this glacier, for to evaluate the contributions of the energy sources much more data is needed encompassing the whole spectrum of weather conditions that occur in this area.

The effect that rainfall has on the surface change of the Ivory has only been touched upon in this dissertation and this could be an area for future research, especially if some means were developed to accurately gauge the temperature of the rain water.

Short period intensive studies would be of great value because they would enable a greater understanding to be gained of the fluctuations in the relative importance and magnitude of the heat fluxes both diurnally and at an even smaller time scale.

There is also a need to obtain more accurate measurements of the surface change and to obtain actual values for the amount of mass lost to evaporation. In fact the possibilities for study on the Ivory Glacier are almost endless.

APPENDIX I

Sensible Heat Flux - solution for terms
(after Longeay (1969, p.91).

$$H = \rho . Cp. \; Kh. \left(\frac{dT}{dZ} + \Gamma\right).$$

where

ρ. is the density of dry air at constant pressure.

Cp. is the specific humidity of air at constant pressure.

Kh. is the coefficient of eddy conductivity.

Γ. is the dry adiabetic lapse rate.

assume $K_n = K_m$.

where (2)

K_m is the coefficient of vertical transfer of momentum.

$$K_m = \frac{U_z \cdot K^2 . Z.}{\ln \frac{z}{z_o}} \qquad (3)$$

where

U_z is the wind speed at height z.

K^2 is Von Karman's constant.

z is the height above the surface.

z_o is the roughness length.

Substituting equation (3) into equation (1) and ignoring Γ. since this number is negligible we get :-

$$H = \rho . Cp. \; \frac{U_z . K^2 . Z}{\ln \frac{z}{z_o}} \; \frac{dt}{dz}. \qquad (4)$$

All the terms in equation (4) can be measured except Z_o continuing the assumption of neutral stability.

Then from logarithmic law

$$\log Z_o = \frac{U_2 \cdot \log Z_1 - U_1 \cdot \log Z_2}{U_2 - U_1} \qquad (5)$$

where

Un is the wind speed at height n

log is the common logarithm (base 10).

Substituting equation (5) into equation (4) we get

$$H = \frac{\rho . Cp. \; U_z . \; K^2 . \; Z.}{\ln \left[\frac{Z}{\text{antilog} \left(\frac{U_2 . \log z_1 - U_1 \cdot \log z_2}{u_2 - u_1}\right)}\right]} \cdot \frac{dT}{dz} \qquad (6)$$

Solving for limits Z_1 and Z_2 to avoid specifying boundary conditions at the surface

$$H = \frac{\rho . Cp. U_2. K^2. (T_2 - T_1.)}{\ln \frac{z_2}{z_o} . \ln \frac{z_2}{z_1}} \qquad (7)$$

where

ln is the natural logarithm (base 2.718).

For given periods at time $\ln \frac{z_2}{z_{o_2}} . \ln \frac{z_2}{z_1}$ can be treated as a constant and Cp., ρ and K^2 may be treated as constants. Thus :

$$C = \frac{Cp. K^2}{\ln \frac{z_2}{z_o} . \ln \frac{z_2}{z_1}} \qquad (8)$$

Then $$H = C. U_2. (T_2 - T_1). \qquad (9)$$

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